Introduction to Spread Spectrum

1997 ARRL/TAPR
Digital Communications Conference

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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

- \textit{Correlation} is a time-averaged product of two input functions
- Mixers and product detectors are analog correlators

\begin{figure}
\centering
\begin{tikzpicture}
\node (f1) at (0,0) {$f_1(t)$};
\node (mult) at (2,0) {mult};
\node (f2) at (4,0) {$f_2(t)$};
\node (lpf) at (6,0) {LPF};

\draw[->] (f1) -- (mult);
\draw[->] (mult) -- (lpf);
\draw[->] (lpf) -- (f2);
\end{tikzpicture}
\end{figure}
Orthogonality

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

\[ f_1(t) \times f_2(t) \]
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 $H_4$:
  
  $\begin{array}{cccc}
  -1 & -1 & -1 & -1 \\
  -1 & +1 & -1 & +1 \\
  -1 & +1 & -1 & +1 \\
  -1 & -1 & +1 & +1 \\
  -1 & +1 & +1 & -1 \\
  \end{array}$
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: $\text{BW\{RF\}} / \text{data rate}$
- Power control is needed to minimize interference and maximize capacity
Spread Spectrum - the traditional view

data in → code → modulate → spread → RF out

RF in → despread → demod → decode → data out
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

Baseband signal $s(t)$

Mixer

Spread signal $s(t)p(t)$

PN generator

Process gain $\frac{\text{BW}[p(t)]}{\text{BW}[s(t)]}$;
$\text{BW}[p(t)] \gg \text{BW}[s(t)]$
Frequency Hopping

baseband signal
\( s(t) \)

mixer

spread signal
\( s(t)\cos([w+ap(t)]t) \)

\( \cos([w+ap(t)]t) \)

PN gen

DDS

\( p(t) \)
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 impractically 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

amplitude

-1 chip +1 chip code 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

X BPF BPF (O^2)

early

X BPF pn gen (O^2)
on-time

X BPF (O^2)
late

+ -
Tau-dither Tracking Loop

VCO

pn gen

mix

BPF

LPF

dith gen

()²

+/-

freq

phase
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

rx 1

rx 2

rx 3

searcher

combiner
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

- \( r = \frac{1}{3} \) 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