INITIAL ACQUISITON

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OUTLINE

- Introduction and System Model
- Quantitative Analysis
- Using Pre- and Post-detection Integration and Optimality
- Practical Design Considerations
- Examples of Initial Acquisition in Wireless Communications
- Summary

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INTRODUCTION AND SYSTEM MODEL

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Receiver Synchronization Process

- Initial Acquisition
- Timing initial acquisition
- Fine initial acquisition
- Time tracking
- Frequency tracking
- Setting other receiver functions related to synchronization

Note: This presentation will focus on initial acquisition, the carrier and timing synchronizations will be covered in subsequent presentations

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Objectives of Initial Acquisition

- Find out if a desired signal exists
- Determine the starting point of a data block (frame synch)
- Determine signal level
  - AGC Initialization
- Determine coarse timing
  - Timing tracking loop initialization
- Determine coarse frequency offset
  - Frequency tracking loop initialization

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Signal Detection in Initial Acquisition

- Generally it can be modeled as detection of a known signal in additive, white Gaussian noise (AWGN)
- The timing of the signal to be detected is unknown, in general
- The phase of the channel is usually unknown
- The channel may be static or time variant, single path or multipath
  - The static single path channel is most important
- It is a typical problem in detection theory

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Signal Model in Initial Acquisition

- Consider a sampled digital system, at time kT, the received signal sample can be expressed as

$$r_k = h_k e^{j\phi_k} s_k + z_k$$

  - Assume that the complex channel gain $h_k e^{j\phi_k}$ in a given time interval does not change
  - s_k is a known, usually BPSK or QPSK, sequence
  - SNR of r_k is equal to $|h_k|^2 / \sigma_z^2$, where σ_z^2 is the variance of z_k, assuming $|s_k|^2 = 1$
  - Multiple samples are (coherently) combined by correlating $\{s_k\}$ with $\{r_k\}$ to form a detected symbol with no-loss of information
  - Detected symbols can be non-coherent combined
  - Both are for improving the detection reliability

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The Detection Process

(1) Correlating s_k with r_k, assuming h and $e^{j\phi}$ do not change, we have

$$d_n = \sum_{k=n}^{n+K-1} s_k^* r_k = \sum_{k=n}^{n+K-1} h_{c,k} e^{j\phi_k} \left|s_k\right|^2 + \sum_{k=n}^{n+K-1} s_k^* z_k = K h_c e^{j\phi} + z'$$

The SNR of d_n is K times of the SNR of r_k $(\gamma_d = K\gamma_r)$

(2) Forming the decision variable

- In most cases, ϕ is unknown: none-coherent detection

$$D_n = \left|K h_c e^{j\phi} + z'\right|^2 = \left|d_n\right|^2$$

(3) Comparing D_n with threshold T

- $D_n < T : \theta = \theta_0 \Rightarrow \text{No Signal}$
- $D_n \geq T : \theta = \theta_1 \Rightarrow \text{Signal sequence } s_n \ldots s_{n+k} \text{ detected!}$

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The Detection Process (cont.)

(4) If no signal, go to samples starting at T_{n+1} or $T_{n+0.5}$, until the detection of signal sequence successful

- Post detection (non-coherent) combining
  - For a time variant channel, the value of *K* is limited by the channel coherent time
  - Performance can be improved by summing multiple D_n's to form a composite decision valuable

$$D_{n,L} = \sum_{l=0}^{L} \left| d_{n+lK} \right|^2$$

  - $D_{n,L}$ is compared to a threshold to perform the same detection as above

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QUANTITATIVE ANALYSIS

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Decision variables' pdfs – without post-detection combining

- D_n above has the following pdfs:
  - No signal ($\theta = \theta_0$) – Central chi-square distribution with 2 degrees of freedom:

$$p_0(D) = \frac{1}{\sigma_{z'}^2} e^{-\frac{D}{\sigma_{z'}^2}}, \quad D \geq 0$$

  - Signal exists ($\theta = \theta_1$) – Non-central chi-square distribution with 2 degrees of freedom:

$$p_1(D) = \frac{1}{\sigma_{z'}^2} e^{-(D+\lambda^2)/\sigma_{z'}^2} I_0\left(\frac{2|\lambda|\sqrt{D}}{\sigma_{z'}^2}\right), \quad D \geq 0$$

$$\lambda = E\left[a_n\right] = K\left|h_c\right| e^{j\phi}$$

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Decision variables' pdfs – with post-detection combining

- $D_{n,L}$ given above has the following pdfs:
  - No signal ($\theta = \theta_0$) – Central chi-square distribution with 2L degrees of freedom:

$$p_{0,L}(D) = \frac{1}{(L-1)!\left(\sigma_{z'}^2\right)^L} D^{L-1} e^{-\frac{D}{\sigma_{z'}^2}}, \; D \geq 0$$

  - Signal exists ($\theta = \theta_1$) – Non-central chi-square distribution with 2L degrees of freedom:

$$p_{1,L}(D) = \frac{1}{\sigma_{z'}^2}\left(\frac{D}{s^2}\right)^{\frac{L-1}{2}} e^{-(D+s^2)/\sigma_{z'}^2} I_{L-1}\left(\frac{2s\sqrt{D}}{\sigma_{z'}^2}\right), \; D \geq 0$$

$$s = \sqrt{\sum_{k=0}^{L-1} |\lambda_k|^2} \qquad \lambda_k = E\left[a_k\right] = K\left|h_{c,k}\right| e^{j\phi_k}$$

I_{L-1} – (L–1)th order Modified Bessel function of the first kind

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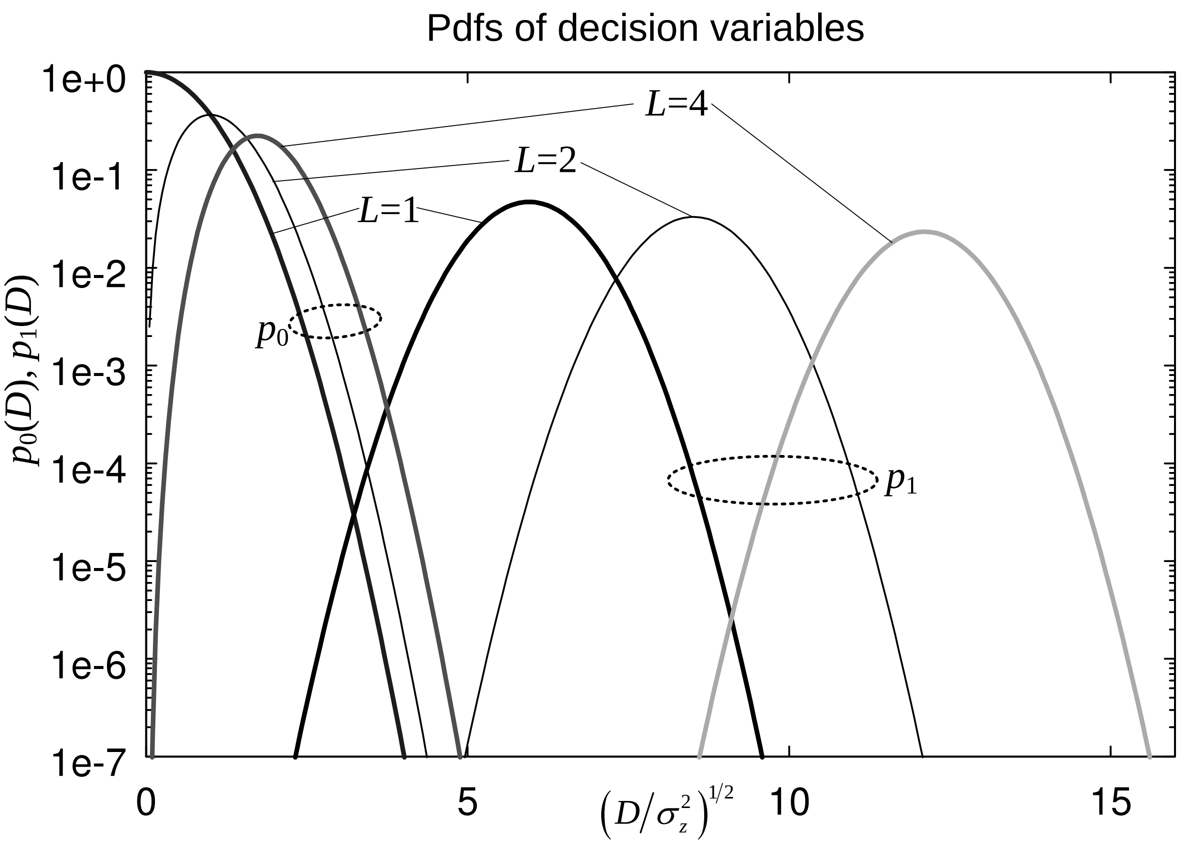
Decision variables' pdfs (cont.)

Assuming all λ_k's are equal



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Detection and false Probability (P_D & P_F)

- False Probability (P_F):

$$P_F = \int_{Th}^{\infty} p_{0,L}(u)du = \int_{Th}^{\infty} \frac{1}{(L-1)!\left(\sigma_{z'}^2\right)^K} u^{L-1} e^{-\frac{u}{\sigma_{z'}^2}} du = e^{-Th} \sum_{k=0}^{L-1} \frac{\left(Th\right)^k}{k!}$$

  - where $Th = Th / \sigma_{z'}^2$ – Normalized threshold

- Detection Probability (P_D):

$$P_D = \int_{Th}^{\infty} p_{1,L}(u)du = \int_{Th}^{\infty} \frac{1}{\sigma_{z'}^2} \left(\frac{u}{s^2}\right)^{\frac{L-1}{2}} e^{-(u+s^2)/\sigma_{z'}^2} I_{L-1}\left(\frac{2s\sqrt{u}}{\sigma_{z'}^2}\right) du$$

$$= \int_{Th}^{\infty} \left(\frac{v}{\tilde{s}^2}\right)^{\frac{K-1}{2}} e^{-(v+\tilde{s}^2)/} I_{L-1}\left(2\tilde{s}\sqrt{v}\right) dv$$

  - where $Th = Th / \sigma_{z'}^2 \quad \tilde{s} = s / \sqrt{\sigma_{z'}^2}$

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P_D, P_{miss} & P_F: Discussion

- P_F only depends on the variance of noise and interference, since there is no signal
- It is more convenient to set threshold based on a predetermined constant P_F
- For the same P_F, the P_D will be larger for a larger L at the same SNR
  - For the same P_D and P_F, double L reduces required SNR by 1.8 – 2.5 dB (the gain is larger at high SNR, see examples below)
- The miss probability is defined as 1 minus the Detection probability ($P_{miss} = 1 - P_D$)

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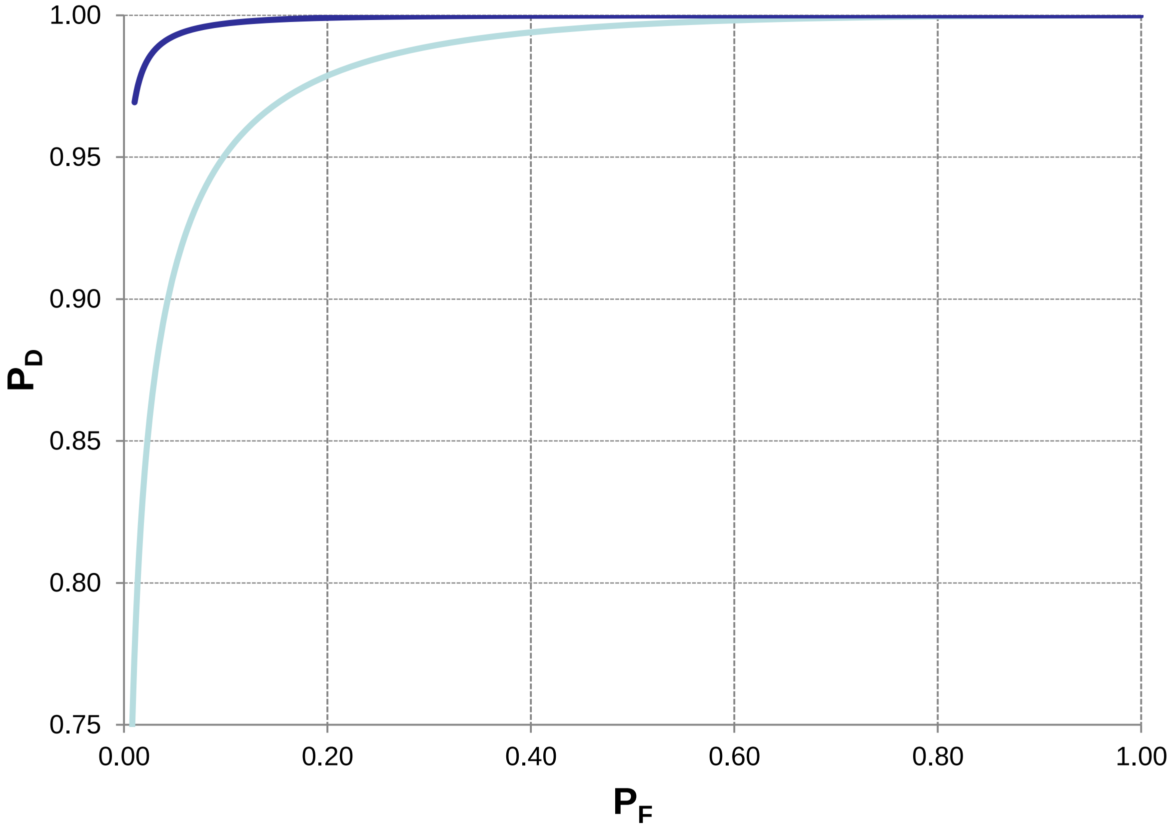
P_D, P_{miss} & P_F – Examples

- P_D vs. P_F L = 1 and 2 for the same SNR (5dB)



P_D, P_{miss} & P_F – Examples (cont.)

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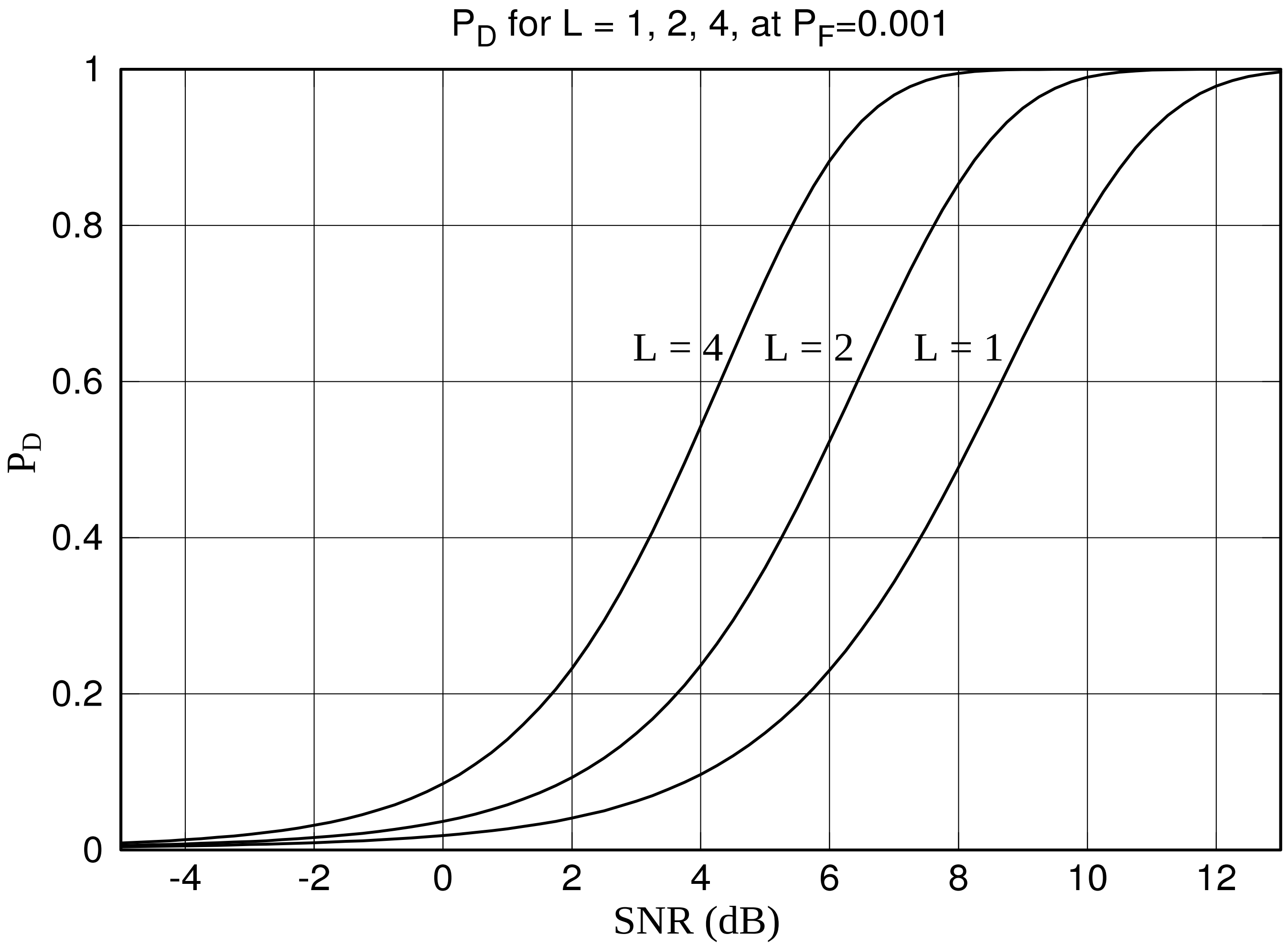

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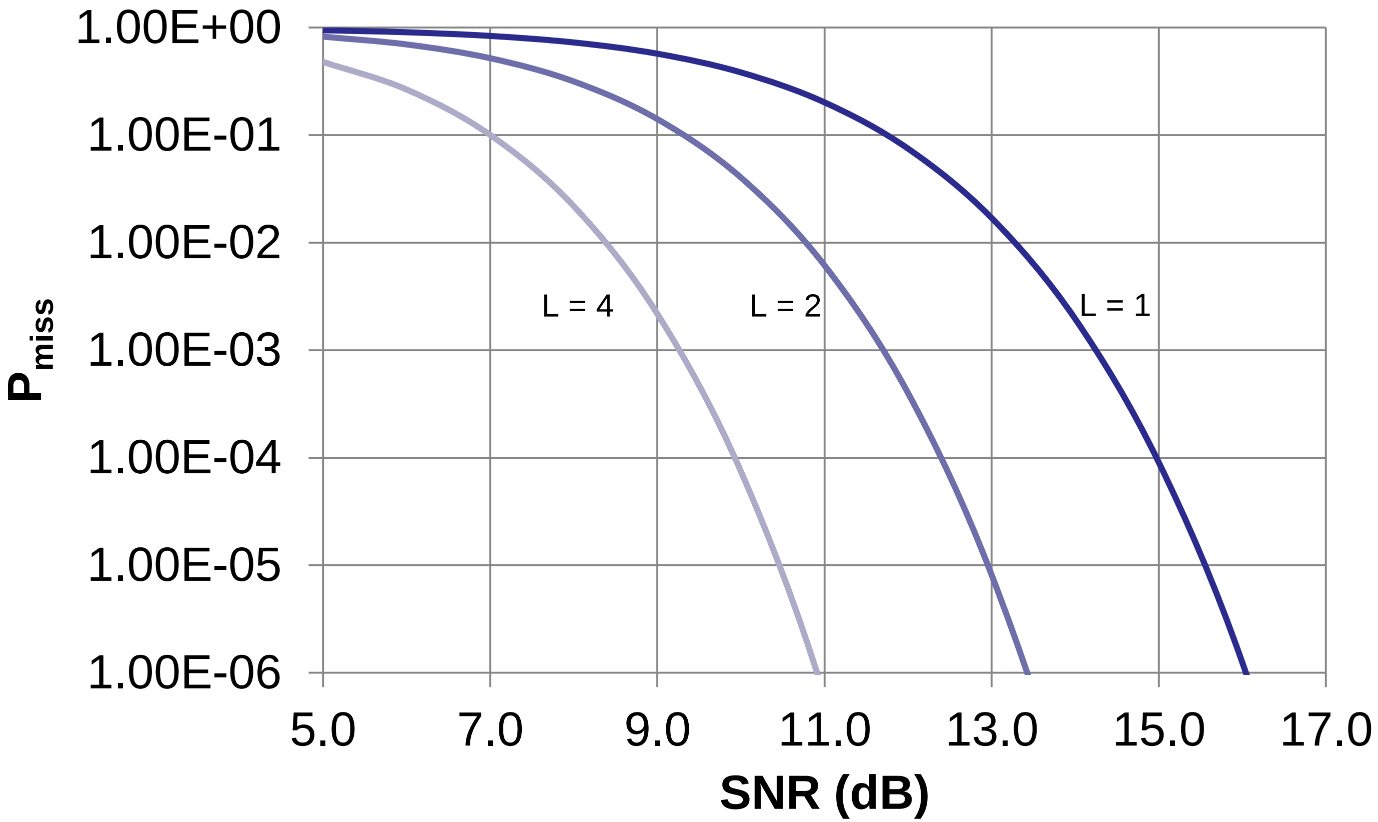
P_D, P_{miss} & P_F – Examples (cont.)

- P_{miss} for L = 1, 2, 4 @P_F = 0.0001 (high SNR)



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USING PRE- AND POST-DETECTION INTEGRATION AND THEIR OPTIMARITY

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Pre-detection integration

- Pre-detection coherent integration (correlation)

$$a_n = \sum_{k=n}^{n+K-1} s_k^* r_k = \sum_{k=n}^{n+K-1} h_{c,k} e^{j\phi_k} \left|s_k\right|^2 + \sum_{k=n}^{n+K-1} s_k^* z_k = K h_c e^{j\phi} + z'$$

- Assuming phase and magnitude do not change: Coherent combining
- 3 dB gain when the samples in integration double
- For time-varying channel the maximum number of samples in coherent integration are limited
- In the simplest case, if there is a frequency offset
  - the integrated signal energy will reduced (combing loss)
  - The lost energy becomes an additional interference
- The combining gain is less than 3 dB for doubling samples

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Pre-detection integration (cont.)

- The coherent integration operation can be viewed as signal passing through a rectangular MA filter with frequency response:

$$H(f)=\frac{\sin\left(\pi KTf\right)}{\pi KTf}=\text{sinc}(\pi KTf)$$

- Assuming frequency offset is f_{offset} the combined energy is equal to

$$K^2\,|h_c|^2\,\text{sinc}^2(\pi KTf_{offset})$$

- Loss is equal to $10\log\left[\text{sinc}^2(\pi KTf_{offset})\right]$
- The interference due to the reduced energy is equal to

$$K^2\,|h_c|^2\times\left(1-\text{sinc}^2(\pi KTf_{offset})\right)$$

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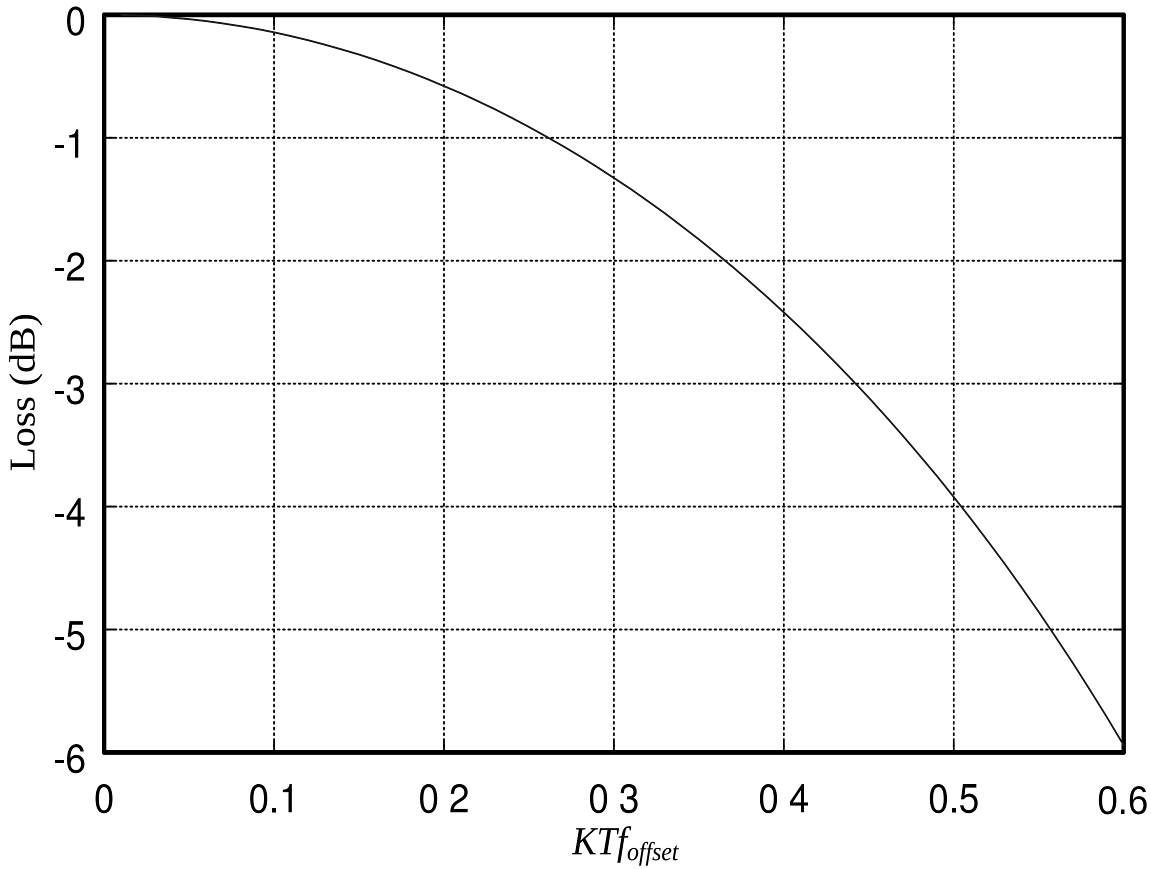
Loss in coherent integration due to frequency offset



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Post-Detection Integration

- As shown above, the combining gain is about 2 dB for post-detection integration if the number of samples doubles in the integration at relatively low SNR
- At high SNR, the gain can be up to 2.5 dB
- It is necessary to determine the parameters for post- and integration based on the channel coherent time and/or frequency offset

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Optimal Detection for Unknown Channel Phase

- Above we described initial acquisition procedure by comparing the squared value of the coherently integrated descrambled samples (with or without non-coherent integration) to a threshold.
- This procedure is not only convenient but also optimal when the channel phase is unknown but uniformly distributed between 0 and 2π.
- In order for it to be optimal, we need to show that this procedure satisfies the Neyman-Pearson lemma with likelihood testing
- We can prove this in three steps

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Can We Argue It Is Optimal?

(1) Neyman-Pearson lemma for binary hypnosis test:

$$\Lambda(y) = \frac{p_1}{p_0} \begin{cases} > \eta : \theta = \theta_1 \\ \leq \eta : \theta = \theta_0 \end{cases}$$

- $\Lambda(y)$: Likelihood ratio, p_1, p_0, pdfs (likelihood functions) of received signal with/without desired signal, η: threshold
- It is optimal in the sense if $\Lambda(y) \leq \eta$ we have P_F equals to a given probability, then P_D is maximized
- Does the detection procedure discussed satisfies the N-P lemma? Two questions need to be answered:
  (1) Are $p_0(D)$ and $p_1(D)$ used in detection the likelihood functions based on the observed received signal ?
  (2) Does comparing D to a threshold equivalent to compare $\Lambda(y)$ to η?

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Can We Argue It Is Optimal? (cont.)

(2) The coherent integration output when signal exists is

$$d_n = K\left|h_c\right|e^{j\phi_n} + z'$$

- with ϕ uniformly distributed between 0 and 2π, the pdf of d_n averaged over ϕ_n is

$$p_1(d_n) = \frac{1}{\sigma_{z'}^2} e^{-(D+|\lambda|^2)/\sigma_{z'}^2} I_0\left(\frac{2|\lambda|\sqrt{D}}{\sigma_{z'}^2}\right), \text{ where } (D = |d_n|^2)$$

- If signal does not exist, i.e., the noise only case, the pdf is:

$$p_0(d_n) = e^{-D/\sigma_{z'}^2} \Big/ \sigma_{z'}^2$$

- Conclusion: $p_0(D)$ and $p_1(D)$ are the averaged pdfs (likelihood functions) of the coherent integrator outputs (before squaring!) with and without signal, respectively

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Can We Argue It Is Optimal?(cont.)

(3) The likelihood ratio Λ is a monotonically increasing function of *D*

- *Th* can be selected such that *D* <> *Th* is equivalent to Λ <> h

- Proof of detection with post-detection integration is similar

Notes:

- We have shown in what sense the detection process is optimal
- However, the optimality in the area of statistics is always arguable ☺

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PRACTICAL DESIGN CONSIDERATIONS

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Noise Variance Estimation

- Noise variance estimate is the key for setting accurate detection thresholds
  - Accuracy of the estimate determines if the detection performance meets design expectation
- Examples of noise estimation
  - Very low SNR environment, e.g., CDMA voice systems (IS-95, IS-2000)
    - Total noise power is approximately equal to total power
    - With AGC, the total power is approximately a constant

    => The noise power is a constant

    => Threshold determined by AGC setting

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Noise Variance Estimation (cont.)

- Examples of noise estimation (cont.)
  - Medium to high SNR Environment
    - Total power at AGC output is equal to signal power plus noise power ($P_s + P_n = A$)
    - After correlation with the expected sequence:
      - With no desired signal: $E[D_n] = KE[|a_n|^2] = KP_n$
      - With desired signal:
        $$E[D_n] = KE[|a_n|^2] = K^2 P_s + KP_n = B$$
      - Then $P_n = \left(\frac{AK^2 - B}{K(K-1)}\right)$ if $K >> 1,\ P_n \approx A - \frac{B}{K^2}$
      - Comments:
        - » Estimation of A is usually more accurate due to averaging
        - » With post detection integration, the estimate can be improved by averaging multiple D_n's

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Noise Variance Estimation (cont.)

- Further discussions:
  - For detection, the accuracy of estimation of noise variance has ultimate importance.
  - Noise variance estimation can be improved if there are known orthogonal spaces in which only contains noise but no known signal, e.g.,
    - Different frequencies
    - Different Walsh code spaces
    - “Blank out” time intervals
  - Need to make sure the noises in these orthogonal spaces has the same variance as that we want to estimate for using the hypothesis testing

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P_D and P_F Parameter Selection

- The target of P_F usually selected to be much smaller then P_{miss}, i.e., 1 - P_D
  - Many possible false events would occur for one detection event, for example:
    - In CDMA-2000 initial acquisition, for each θ_1, there could be 32767 offsets (or 65534 for half chip sampling) to result θ_0
    - For WCDMA need to try many false hypotheses to find the true P-SCH and S-SCH in addition to time offset hypotheses
      - Many effort have been made to reduce the search effort (mainly hierarchical cell-search). However there are still a lot of hypotheses to test.
    - LTE also uses hierarchical cell-search approach (PSS and SSS). Thus, there are also a lot of hypotheses to test

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P_D and P_F Selection (cont.)

- On the other hand, rejecting a false alarm event is usually easier than correcting a miss event
  - False alarm event may be verified by additional correlations of the same sequences with different offset
    - However, false event with additional processing may cause missing the opportunity of acquiring the signal
  - To acquired the right detection again, the acquisition need to be performed one more cycle

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P_D and P_F and Acquisition Performance

- The acquiring process can be expressed by a state machine
- The acquisition performance depends on:
  - The costs of verifying a wrong test results
  - The costs needed before next successful acquisition
  - Costs include the needed time and processing power consumption
- The average power and time for a successful acquisition can be computed based on P_D, P_F and the associated cost.
- Parallel processing can reduce acquisition time but not power consumption

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Dealing with Large Initial Frequency Offset

- It would be desirable to use (low cost) XOs with high initial frequency error, which will impact initial acquisition performance
- Shorter coherent integration length can be used followed by longer non-coherent post-detection integration
  - Acquisition time will be longer, or P_D and/or P_F will be larger
  - Coherent integration length cannot be too short due to aperiodic integration loss
- Another method is to use multiple initial frequency hypnoses
  - Setting initial frequencies to be 0, $\pm\Delta F_h$, $\pm 2\Delta F_h$, … reduces the maximum initial frequency offset to $\pm 0.5\Delta F_h$
    - This will increase computational complexity of acquisition
    - May also increase initial acquisition time

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EXAMPLES OF INITIAL ACQUISITION IN WIRELESS COMMUNICATIONS

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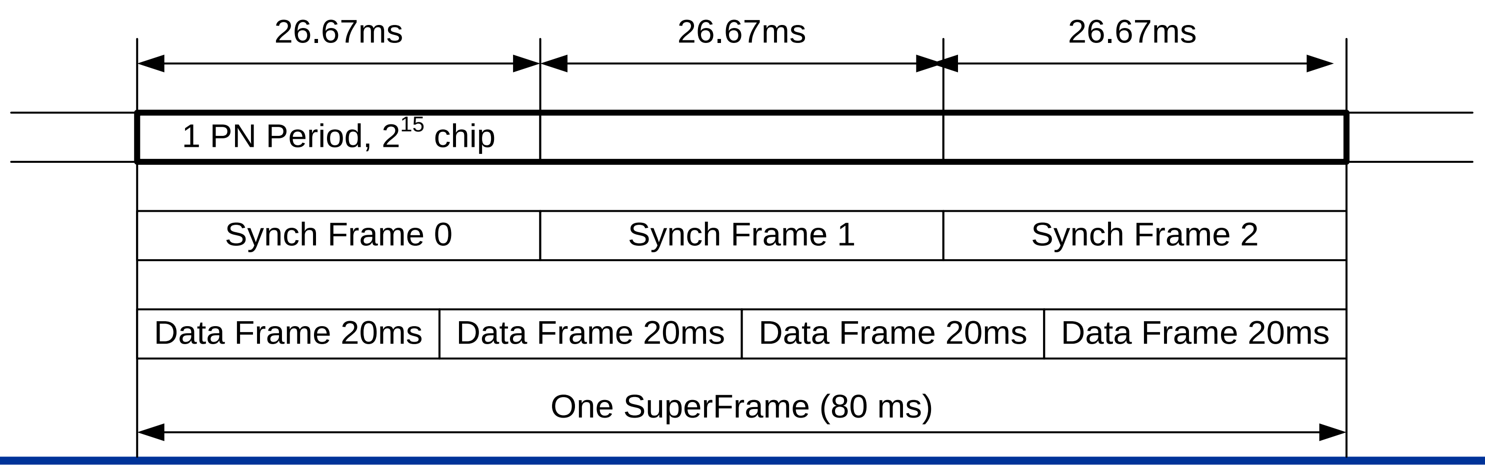
CDMA-2000

- It's pilot channel is used for initial acquisition
- Pilot channel signal is periodic with period (26.6667 ms long) of 32768 with QPSK modulation (with a pair of augmented 2^{15}–1 long PN sequences known to receiver)
- Three period of the pilot channel constitutes an 80 ms Superframe, which contains 3 26.67 ms Synch frames and 4 20 ms data frames



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CDMA-2000 (cont.)

- To detect the pilot channel, the receiver correlates the received signal with one or more segments of the sequence.
- The received signal should be sampled more than once per sample (chip) interval, usually, 0.5 chip interval, i.e., 2 correlations per one chip interval is appropriate
- For parallel processing and/or post-detection combining, segments of the PN sequence can be used to correlate with the same or different signal sequences
- Once a match is found, the receiver knows the beginning of the PN sequence
- A PN sequence period aligns with a frame of sync channel

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CDMA-2000 (cont.)

- Once the beginning of PN sequence, the receiver demodulate the synch channel to determine the start of the Superframe and information for demodulating other forward link channels
- Selection of coherent integration length:
  - Assume we have initial frequency accuracy of 2ppm ($2x10^{-6}$)
  - For 800 MHz band, the frequency offset is 1600 Hz
  - The CDMA2000 chip rate is 1.2288 Mchips/sec
  - If we choose to integrate 100 chips, we will have a loss of

$$10\log\left[\text{sinc}^2(\pi*100*1.2288*10^{-6}*1600)\right]=-0.64dB$$

  - For 1.9G band, the integration will be 40 chips to have the same loss
- Multiple such coherent integrated outputs could be non-coherently combined

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WCDMA

- WCDMA employs a two stage initial acquisition procedure with two Synchronization Channels:
  - Primary Synchronization Channel (P-SCH)
    - Utilize a 256 chip spreading sequence
    - Same for all of the cells
  - Secondary Synchronization Channel (S-SCH)
    - Each cell transmits one out of 64 possible S-SCH codes
    - Each S-SCH codes is a combination of 15 different sequences, each of which is from a group of 16 256 chip sequences
- WCDMA SCH channel structure is as shown below

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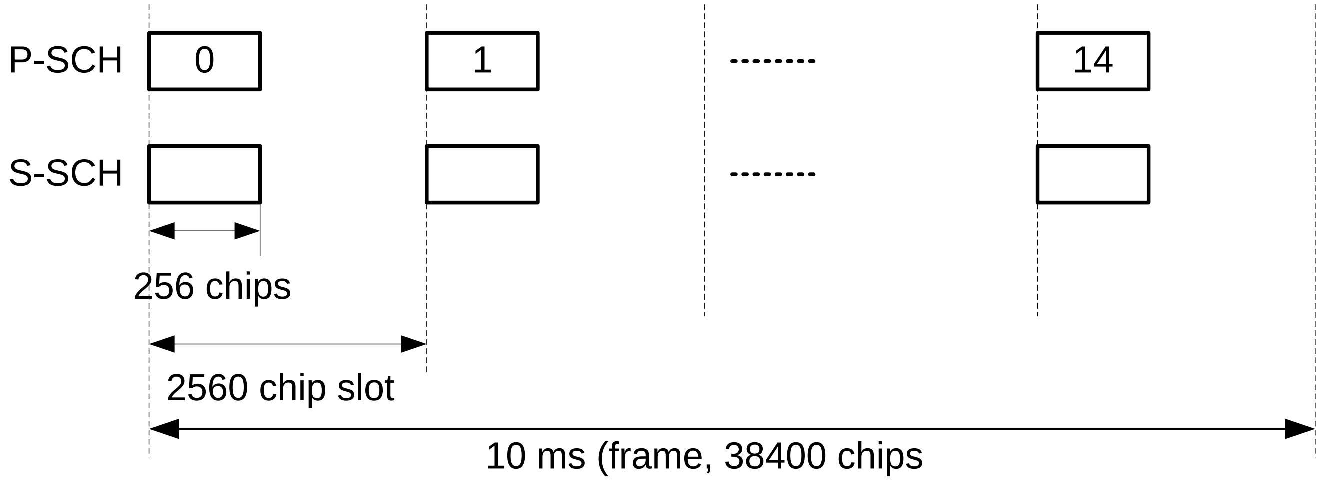
WCDMA (cont.)



- Acquisition process:
  - First search for P-SCH
    - 256 chip (@ 3.84 MHz =66.67 μs) coherent integration
    - Non-coherent combining of coherent integration output may be used.
    - Successful P-SCH search determines slot boundary

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WCDMA (cont.)

- Acquisition process (cont.)
  - Search for S-SCH
    - Determine S-SCH code sequences at slot boundaries by correlating all 16 possible 256 S-SCH chip sequences
    - The largest peaks at the correlator output determines the S-SCH chip sequences transmitted by the cell
    - Match the determined chip sequences to one of the 64 possible S-SCH code words (may need to check 15 start positions)
    - Once the S-SCH code word is determined, the receiver knows the frame boundary
    - Search for primary scrambling codes of the pilot and data channels (Each S-SCH code word corresponding to a code group with 8 scrambling codes)

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LTE

- LTE has 6 possible transmission signal bandwidths: 1.4, 3, 5, 10, 15 and 20
- LTE has FDD (discussed here) and TDD modes
- To facilitate the initial acquisition, the synch channel bandwidth is 1.4 MHz (72 subcarriers, 62 non-zero data).
  - For wider bandwidth transmission, the synch channels occupy the center 72 subcarriers (73 including the zero subcarrier).
- Similar to WCDMA, LTE employs a two stage initial acquisition procedure using two Synch Channels:
  - Primary Synchronization Channel (P-SCH or PSS)
  - Secondary Synchronization Channel (S-SCH or SSS)
    - PSS and SSS occupies one OFDM symbol each
    - A pair of PSS and SSS symbols are transmitted every 5 ms

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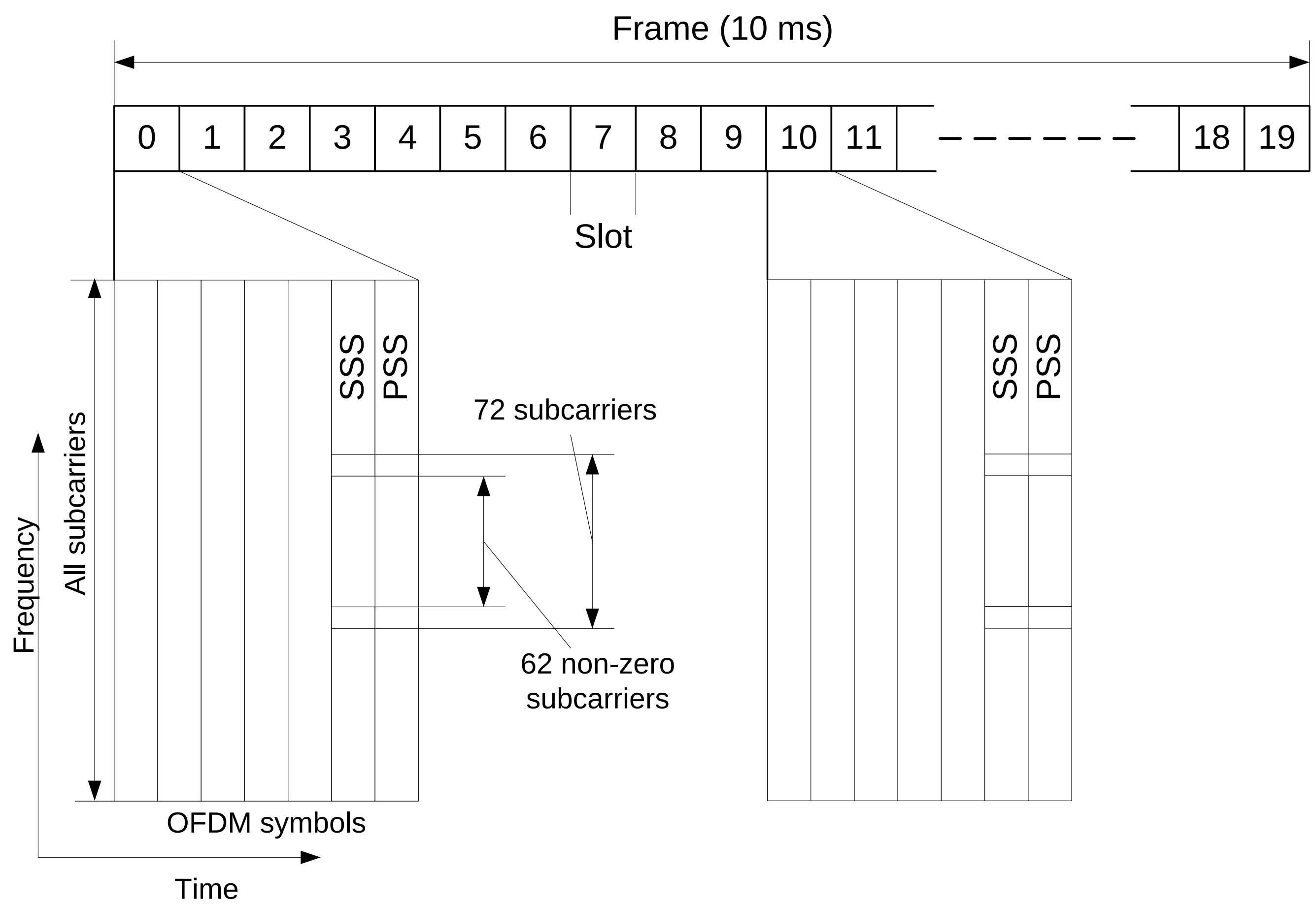
LTE (Cont.)

- PSS OFDM Symbol
  - It is generated from a frequency domain Zadoff-Chu sequence with two 32 long segments
    - Constant Amplitude (low peak to average power ratio)
    - Impulse (time domain) autocorrelation
    - There are three such PSS symbols ($N_{ID}^{(2)} = 0, 1, 2$)
  - It is the last OFDM symbol in the 0th and 10th slot
- SSS OFDM Symbol:
  - Consists of 2 interleaved length-31 m-sequences, each of which has a different cyclic shift
  - There are 168 such SSS OFDM symbols ($N_{ID}^{(1)} = 0, 1, ..., 167$), with combinations of different shifts
  - scrambled according to $N_{ID}^{(2)}$
  - There are a total of 504 cell ID's: $N_{ID}^{cell} = 3N_{ID}^{(2)} + N_{ID}^{(1)}$
  - It is the OFDM symbol proceeding PSS

LTE (Cont.)

- PSS and SSS in time and frequency



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LTE (Cont.)

- PSS Acquisition:
  - Even though PSS is defined in frequency domain, the detection is most efficient done in time domain.
  - The total data bandwidth of PSS is 945KHz, the signal can be first filtered to between 0.945 to 1.08 MHz and down sampled
  - The down sampled signals are correlated the three possible sample sequences of the time domain representations of PSS
    - OFDM symbol length is 67μs so coherent combining can be used
  - The correlator output are squared, likely non-coherently combined with multiple such output spaced by 5 ms, and compared to a threshold.
  - Such hypothesis testing need to performed every 0.5 sample interval until a success is declared
  - This determines the half frame boundary and the cell ID $N_{ID}^{(2)}$

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LTE (Cont.)

- SSS Detection:
  - The scramble code of SSS is know with $N_{ID}^{(2)}$ from PSS detection
  - The received signal corresponding to SSS position is correlated with the 168 time domain representations of SSS
  - The largest correlation outputs determines the cell ID
  - The frame boundary is determined by based on SSS
    - The zeroth and 10th SSS has the same two 31 sequences but swapped in place
  - Non-ideal cross-correlation property between SSS sequences may require extra steps to reduce the false probability
- Cell ID (PSS and SSS) determines the scrambling sequences of other channels

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Further Discussions

- In a multipath channel a moving average filter of the squared detection outputs as the decision variable may provide a better detection probability
- The received signal sample sequence that passed the detection hypotheses can provide a rough timing estimate
  - In LTE, the timing will need to be refined if the data bandwidth is wider than the PSS/SSS bandwidth, i.e., 1.4 MHz
- The phase differences between the consecutive correlation outputs can provide an estimate of the carrier phase shift between them and thus frequency offset
- These conclusions can be used for all of the three examples discussed above
  - Due to the large number of possible bands for LTE deployment, pre-PSS frequency scanning may be necessary to determine which bands contain valid LTE signals

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SUMMARY

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- Initial acquisition is usually done by the receiver trying to find a known sequence sent at regular interval by Tx
- The detection is done by correlating a know transmitted sequence with the received signal samples and the squared outputs are compared to a threshold for detection
- The theoretical pre-detection (coherent) and post-detection (non-coherent) characteristics were derived
- The coherent and non-coherent combining performances were shown and their trade-offs were discussed
  - It is shown numerically, post-detection (non-coherent) combing has about 2 dB gain or higher when samples are doubled
  - In theory pre-detection (coherent) combing has a 3 dB gain or when samples are doubled. However, the gain is reduced when channel is time-varying

- It is shown the square detection metrics are optimal in statistical sense
- Practical design considerations were discussed
- Three examples of wireless communication initial acquisitions were presented, including CDMA2000, WCDMA and LTE
- Initial acquisition can provide initial estimates for receiver frequency, timing and AGC blocks
- Only the simplest case of single path static AWGN channel was discussed, because:
  - It can be used base-line for system design and accurate verification of receiver performance in simulation and lab testing
  - It is the foundation of system initial acquisition for more complex system models
  - Special considerations must be given for specific systems, e.g. LTE, especially TDD LTE

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