Robust Synchronization for DVB-S2 and OFDM Systems

PhD Viva Presentation

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Introduction (1/2)

• **A current trend in modern wireless communications**
  – High capacity applications (i.e. broadband)
  – User mobility

• **DVB-S2 addresses broadband in geostationary satellite applications**
  – Advanced modulation and coding techniques
  – Operation at very low SNR (e.g. -2dB)
  – TV and Internet applications

• **OFDM addresses broadband in terrestrial and satellite-terrestrial-hybrid applications**
  – Robust against frequency-selectivity in channel
  – Increased bandwidth efficiency
  – Many wireless standards (Wi-Fi, WiMAX, DVB-SH etc.)
Introduction (2/2)

- **Carrier Frequency Synchronization**
  - Frequency offsets caused by
    - Local Oscillator (LO) instabilities/inaccuracies
    - Doppler effects
  - Carrier frequency recovery
    - Needed to achieve optimum BER
    - Tougher in wideband channels due to delay spread

- **Frame/Symbol Timing Synchronization**
  - Frame detection for burst modes
  - Accurate positioning of FFT window
    - Otherwise ISI will lead to BER degradation
Single Frequency Estimation

• Complex sinusoid embedded in complex AWGN

\[ x_t = A e^{j(2\pi f_0 t + \theta)} + n_t; \quad t = 0, 1, 2, \ldots, N - 1 \]

  – Data record containing \( N \) samples
  – Frequency measured as a fraction of the sampling rate
  – Theoretical estimation range: \( f_0 = 50\% \)
  – Cramer-Rao lower bound (CRLB) defined for estimation variance

• ML Estimator

  – Determined by searching for the peak of a periodogram

\[ \hat{f}_0 = \frac{1}{N'} \arg \max_{-N'/2 \leq f' < N'/2} \left\{ \sum_{t=0}^{N-1} x_t e^{-j2\pi f't/N'} \right\}^2 \]

  – Achieves CRLB even at low SNR with full estimation range
  – Computationally-intensive due to the high resolution required for accuracy
Existing Methods

- **Kay’s method (WPA)**
  - **Weighted Phase Averager**
    \[
    \hat{f}_0 = \frac{1}{2\pi} \sum_{t=1}^{N-1} w_t \angle \{ x_t x_{t-1}^* \}
    \]
  - Low complexity, achieves CRLB at moderate/high SNR
  - SNR threshold below which accuracy degrades significantly
  - Full estimation range not achieved e.g. \( f_0 < 20\% \)

- **Mengali and Morelli (M&M)’s method**
  - Weighted Autocorrelation Phase Averager
    \[
    \hat{f}_0 = \frac{1}{2\pi} \sum_{m=1}^{M} w_m \angle \{ R(m) R^*(m-1) \}; \quad R(m) \triangleq \frac{1}{N-m} \sum_{t=m}^{N-1} x_t x_{t-m}^*
    \]
  - Practical complexity, achieves CRLB at low SNR
  - Full estimation range not achieved e.g. \( f_0 < 30\% \)
Proposed Methods

- **WNLP**
  - Weighted Normalized Linear Predictor
  - Kay’s signal model revised
    - Frequency is related to signal phase, not amplitude: normalize signal
    - Perform signal averaging before ‘hard’ angle operation
      - Reduces complexity and increases robustness against angle ambiguity
  - Full estimation range with complexity lower than Kay’s WPA

\[
x_t = Ae^{j(2\pi f_0 t + \theta)} + n_t
\]

\[
\hat{f}_0 = \frac{1}{2\pi} \angle \left\{ \sum_{t=1}^{N-1} w_t \bar{x}_t \bar{x}_{t-1}^* \right\}; \quad \bar{x}_t = x_t / |x_t|
\]

- Full estimation range with complexity lower than Kay’s WPA

- **WNALP**
  - Weighted Normalized Autocorrelation Linear Predictor
  - Similar concept to WNLP

\[
\hat{f}_0 = \frac{1}{2\pi} \angle \left\{ \sum_{m=1}^{M} w_m \bar{R}(m) \bar{R}^*(m-1) \right\}; \quad \bar{R}(m) = R(m) / |R(m)|
\]

- Full estimation range with complexity lower than M&M’s method
Simulation Results

- $N=24$, $N'=1024$
- Complex multiplications: MLE (10,240), WNALP (234)

![Graphs showing frequency MSE vs. SNR for different methods at $f_0=0.05$ and $f_0=0.45$.](graph.png)
**DVB-S2 Frequency Synch**

- **DVB-S2 PL frame structure imposes stringent frequency accuracy requirement**
  - Pilot fields periodically inserted for frequency and phase synch
  - Target $\Delta f << 0.34\%$: Not achievable by 1 pilot field of 36 symbols
  - Necessitates use of signal averaging over many pilot fields

- **DVB-S2 systems tolerate large carrier frequency offsets**
  - Up to 5MHz @ 25Mbaud (i.e. $\Delta f \leq 20\%$)

- **Casini et al proposed two stages of DVB-S2 frequency synch**
  - Closed-loop FED for coarse frequency ($\Delta f \leq 20\%$)
    - 1650 pilot fields used (equivalent to 100ms at 25Mbaud)
  - Modified L&R’s method for fine frequency ($\Delta f \leq 1\%$)
    - 1000 pilot fields used (equivalent to 60ms at 25Mbaud)

- **Signal model for novel WNALP not valid at very low SNR**
  - Averaged WNALP uses the autocorrelation sum over multiple pilot fields at a fixed lag to boost the effective SNR
Simulation Results

- $N=36$ training symbols, AWGN channel
- Same accuracy achieved by AWNALP and Modified L&R
  - AWNALP achieves faster DVB-S2 synch: coarse stage avoided!

![Normalized Frequency MSE graphs](image)

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OFDM Synchronization

• **OFDM modulation**
  - Transmission using many orthogonal sub-carriers
  - Efficient implementation via FFT algorithm
  - Guard time/cyclic prefix inserted to cope with channel delay spread

\[ x_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N_{\text{use}}-1} X_n e^{j2\pi kn/N}; \quad k = 0,1,2,3,\ldots,N-1 \]

  Transmitted signal

\[ r(k) = \sum_{m=0}^{L-1} h(m) x(k - \varepsilon - m) e^{j2\pi \Delta f k / N} + \omega(k) \]

  Received signal

• **Due to orthogonality requirement**
  - OFDM is very sensitive to carrier frequency errors
  - OFDM is quite sensitive to symbol timing errors
    - Timing estimates must fall within the ISI-free region
Existing methods: Frequency

- **Fractional frequency estimation**
  - Use of autocorrelation over identical blocks
    - Each block is longer than the channel delay spread
    - Necessary in ISI channels for acceptable fractional accuracy
- **Fractional + Integer frequency estimation**
  - Morelli’s method
    - 1 OFDM training symbol used, limited estimation range
  - Schmidl’s method
    - 2 OFDM training symbols used, wide estimation range
    - Metric complexity: Order \(N^2\)
  - Kim’s method
    - 1 OFDM training symbol used, wide estimation range
    - Metric complexity: Order \(N^2\)
Existing methods: Timing

- **Autocorrelation techniques**
  - Traditional approach based on identical blocks
  - Works well under large frequency offsets
  - However, auto-corr timing drifts into ISI region
  - Popular methods
    - **Schmidl**: 1 training symbol with 2 ‘unsigned’ identical blocks
    - **Minn**: 1 training symbol with 4, 8 or 16 ‘signed’ identical blocks

- **Cross-correlation techniques**
  - Sharper detection properties than autocorrelation
  - Coherent x-corr fails under large frequency offsets
  - ISI causes a set of multiple peaks in x-corr metric (good or bad?)
  - Identical blocks produce extra sets of peaks (i.e. detection ambiguity)
Proposed method: Time-Freq

- **Autocorrelation vs. Cross-correlation?**
  - Benefit from both approaches
  - 1 training symbol with 2 identical blocks: Best compromise!

![Graph showing correlation metric values vs. timing error](image)
Proposed method: Time-Freq

- **Use 1 OFDM training symbol with 2 identical blocks**

- **Use low-complexity autocorrelation**
  - Estimate coarse timing and fractional freq. offset
  - Compensate fractional frequency offset

- **Use restricted differential cross-correlation**
  - Can cope with residual integer frequency offsets
  - One symbol interval about the coarse timing
  - Gives an indication of the channel arriving paths but not as strong as coherent x-corr for timing detection
  - Use autocorrelation to filter the ‘false’ sets of peaks
  - Determine a restricted set of likely timing estimates
Proposed method: Time-Freq.

- Filtered restricted differential x-corr in ISI channel
  - \( N=256, \ G=16, \) exponential PDP, \( L=8 \) taps
Proposed method: Time-Freq.

- **Use FFT processing**
  - To implement coherent x-corr at each likely timing estimate (starting from the strongest) over the integer frequency axis
  - Detection of strong peak indicates a **confirmed timing estimate** and the **correct integer frequency offset**
  - Use threshold criterion to mitigate false alarm
  - Use MAX criterion to recover missed detection
  - Full estimation range
  - Metric complexity: Order \( (N \log_2 N) \)
  - Compensate integer frequency offset
Proposed method: Time-Freq.

- Integer frequency offset metric in ISI channel
  - \( N=256, \ G=16, \) exponential PDP, \( L=8 \) taps
Proposed method: Timing

• Use restricted coherent cross-correlation
  – Less than a half-symbol interval preceding the confirmed timing
  – Detect channel impulse response i.e. coherent multipath peaks
  – Track first arriving path (ideal timing) using threshold criterion

Restricted cross-correlation in ISI channel (no AWGN)
  \( N=256, G=16, \) exponential PDP, \( L=8 \) taps
Sim. Results: Timing

- **Timing MSE performance in ISI channel**
  - $N=256$, $G=16$, exponential PDP, $L=8$ taps

![Graph showing normalized timing MSE vs. SNR](image)

- Park
- Proposed
- Schmidl
- Shi
- Minn
Sim. Results: Frequency

- **Frequency MSE in ISI channel**
  - $N=256$, $G=16$, exponential PDP, $L=8$ taps

$N_{use}=256$ subcarriers

$N_{use}=200$ subcarriers
Sim. Results: Time-Freq. (1/2)

- Uncoded BER performance in ISI channel
  - $N=256$, $G=16$, exponential PDP, $L=8$ taps

![Graph showing BER vs. $E_s/N_0$ for different synchronization methods]
• Coded PER in Satellite-Terrestrial-Hybrid ISI channel
  – N=1024, G=64, MAESTRO channel profile 5
  – 3GPP feasibility study on OFDM (includes turbo coding)
Conclusions

• **Single Frequency Estimation**
  – Full estimation range and lower computational complexity

• **DVB-S2 Frequency Synchronization**
  – Reduced synchronization delay while maintaining practical complexity

• **OFDM Timing and Frequency Synchronization**
  – Minimum preamble overhead with simple structure
  – Full frequency estimation range
  – Robust timing and frequency accuracy
  – Low and adaptive complexity
  – Robust in fading ISI channels
  – Optimum BER performance
Publications


✓ Robust and efficient time-frequency synchronization for OFDM systems, Submitted for publication in *IEEE Transactions on Wireless Communications*, 2008.
Any Questions?

THANK YOU