Simulating a Wi-Fi Communication Chain

Course: ELEC-H401

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Introduction

0.1 Context and Objectives

- **Context:**
  - Discuss the evolution of wireless standards, specifically focusing on the requirements of IEEE 802.11ax (Wi-Fi 6) such as high data rates and spectral efficiency.
  - Explain the challenge of multipath propagation in indoor environments and how it leads to frequency-selective fading.
  - Introduce OFDM as the modulation technique of choice to combat ISI and MIMO as the key to increasing capacity and reliability.
- **Objectives:**
  - State the primary goal: to build a comprehensive baseband simulation in Matlab that mirrors a real-world Wi-Fi transceiver.
  - Define specific technical targets: achieving bit-exact transmission in ideal conditions, implementing robust synchronization algorithms, and demonstrating diversity gain with multiple antennas.
  - List the system parameters explicitly: Bandwidth (160 MHz), Subcarriers ($Q = 2048$), Cyclic Prefix ($L_{CP} = 256$), and Carrier Frequency (5 GHz).

0.2 Project Structure

- **Methodology:** Explain the iterative design philosophy—starting from a simple SISO link with perfect synchronization and progressively adding non-idealities (channel, timing offset, CFO) and their corresponding mitigation techniques.
- **Report Organization:**
  - Chapter 2 establishes the foundational OFDM model.
  - Chapter 3 details how the channel is estimated and equalized.
  - Chapter 4 addresses the critical issues of Time and Frequency synchronization.
  - Chapter 5 expands the system to Multi-Antenna (MIMO) configurations.

1

OFDM System Model

1.1 Theoretical Background

1.1.1 Multi-Carrier Principle and Orthogonality

- **Concept:** Explain why we split a high-rate serial stream into N parallel low-rate substreams. Mention that this increases the symbol duration T_s beyond the channel delay spread τ_{max}, reducing the impact of ISI.
- **Orthogonality:** Define the condition for subcarrier spacing ($\Delta f = 1/T$) that allows overlapping spectra without interference at the sampling points.
- **Mathematical Formulation:**
  - Write down the IFFT equation used at the transmitter: $x[n] = \frac{1}{\sqrt{Q}} \sum_{k=0}^{Q-1} X_k e^{j2\pi kn/Q}$.
  - Describe the corresponding FFT operation at the receiver to recover the data symbols.

1.1.2 Cyclic Prefix and Frequency Domain Equalization

- **Cyclic Prefix (CP):** Describe the operation of copying the last L samples to the front of the symbol. Explain its dual role: acting as a guard interval to eliminate ISI and converting the channel's linear convolution into a circular convolution.
- **Key Result:** Derive or state the property that circular convolution in time corresponds to scalar multiplication in the frequency domain: $Y_k = H_k X_k + N_k$. This justifies the use of a simple one-tap zero-forcing equalizer.

1.2 Implementation: The OFDM Transceiver

1.2.1 Simulation Parameters and Architecture

- **Architecture:** Provide a high-level block diagram description of the implemented transceiver (Bits $\rightarrow$ Mapper $\rightarrow$ IFFT $\rightarrow$ CP $\rightarrow$ Channel $\rightarrow$ CP Removal $\rightarrow$ FFT $\rightarrow$ Demapper).
- **Parameters:** Detail the specific values used ($Q = 2048$, $L_{CP} = 256$, Modulation scheme).

1.2.2 Sanity Check: The "Grey Box"

- **Verification:** Describe the test performed with an ideal channel ($H(f) = 1$, no noise).
- **Result:** Confirm that the Bit Error Rate (BER) was exactly 0. This proves that the IFFT/FFT scaling and CP insertion/removal logic are correctly implemented.

1.3 Performance Assessment

1.3.1 AWGN Performance

- Present the plot of BER vs. SNR in an AWGN channel.
- Compare your simulation curve with the theoretical ‘berawgn‘ curve.
- Discuss any deviations; a perfect match validates the noise generation and signal power normalization.

Image Placeholder: BER vs SNR in AWGN Channel (Validation)
filename: ber-awgn-validation.png

Figure 1.1: BER vs SNR in AWGN Channel (Validation)

1.3.2 Multipath Channel and One-Tap Equalization

- Introduce the static multipath channel model used (e.g., ‘h = [1, 0.5, 0.2]‘).
- Show the "cloud" constellation plot before equalization to visualize the effect of multipath scattering.
- Describe the Zero-Forcing (ZF) equalizer implementation assuming Perfect Channel State Information (CSI).
- Show the "corrected" constellation plot, demonstrating how the points converge back to their ideal QAM centers.

Image Placeholder: Constellation: Multipath Scattering vs. Perfect ZF Equalization
filename: constellation-equalized.png

Figure 1.2: Constellation: Multipath Scattering vs. Perfect ZF Equalization

2 Channel Estimation and Equalization

2.1 Estimation Theory

2.1.1 Preamble-Based Estimation

- Explain the realistic constraint: the receiver does not know the channel response H_k.
- Describe the solution: transmitting a "Preamble" consisting of known pilot symbols at the start of the frame.

2.1.2 LS vs. Time-Domain Estimation

- **Least Squares (LS):** Define the estimator $\hat{H}_{LS}[k] = Y_{preamble}[k]/X_{preamble}[k]$. Explain its limitation: it estimates each subcarrier independently, so the estimation error variance is determined solely by the SNR.
- **Time-Domain Estimation:**
  - Explain the insight: the true channel impulse response has a finite length L_{ch} which is much shorter than the symbol length Q.
  - Describe the noise reduction algorithm: IFFT of $\hat{H}_{LS} \rightarrow$ Windowing (keeping only the first L_{ch} samples) $\rightarrow$ FFT.
  - State the theoretical gain: filtering out noise improves the MSE by a factor of roughly Q/L_{ch}.

2.2 Implementation of Estimators

2.2.1 Preamble Construction

- Describe the specific structure of the preamble used (e.g., 2 identical OFDM symbols, BPSK modulated for robustness).

2.2.2 Algorithms Implementation

- Briefly describe the Matlab functions written for both the LS and Time-Domain estimators.
- Mention the window length parameter used for the Time-Domain estimator (typically equal to the CP length).

2.3 Analysis and Results

2.3.1 Estimation Accuracy (MSE)

- Present the plot of Mean Square Error (MSE) of the channel estimate vs. SNR.
- Analyze the results: The Time-Domain curve should be significantly lower than the LS curve, confirming the noise reduction theory.

Image Placeholder: MSE of Channel Estimate: LS vs Time-Domain
filename: mse-channel-estimation.png

Figure 2.1: MSE of Channel Estimate: LS vs Time-Domain

2.3.2 BER Impact of Real Estimation

- Present a plot comparing BER curves for three scenarios: Perfect CSI, LS Estimation, and Time-Domain Estimation.
- Conclusion: Time-Domain estimation yields a BER curve that is much closer to the ideal Perfect CSI lower bound than the LS estimator.

Image Placeholder: BER Performance: Perfect CSI vs LS vs Time-Domain
filename: ber-multipath-comparison.png

Figure 2.2: BER Performance: Perfect CSI vs LS vs Time-Domain

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Synchronization

3.1 Time Synchronization

3.1.1 Theory: Schmidl & Cox Algorithm

- **Problem:** Define Sampling Time Offset (STO)—the receiver doesn't know when the packet starts.
- **Algorithm:** Explain how the algorithm exploits the periodicity of the preamble (two identical halves).
- **Metric:** Define the timing metric $M(d) = |P(d)|^2/(R(d))^2$, explaining the auto-correlation term $P(d)$ and the energy normalization term $R(d)$.

3.1.2 Implementation: Packet Detection

- Describe the simulation setup: inserting a random delay (zeros) before the transmitted packet.
- Explain the sliding window implementation used to calculate $M(d)$ efficiently.

3.1.3 Analysis: Timing MSE and Robustness

- Show the plot of the timing metric $M(d)$ vs. sample index. Point out the characteristic "plateau" or peak at the correct start index.
- Discuss robustness: Explain that as long as the estimated start point falls within the Cyclic Prefix (and before the ISI region), orthogonality is preserved. The only side effect is a linear phase rotation in frequency, which is handled by the equalizer.

3.2 Frequency Synchronization (CFO)

3.2.1 Theory: CFO Effects and Correction

- **Cause:** Attribute CFO to the mismatch between transmitter and receiver local oscillators.
- **Effects:**
  - *Common Phase Error (CPE):* A rotation of the constellation that grows with time.

Image Placeholder: Timing Metric $M(d)$ vs Sample Index
filename: timing-metric-schmidl-cox.png

Figure 3.1: Timing Metric $M(d)$ vs Sample Index

- *Inter-Carrier Interference (ICI):* Loss of orthogonality, behaving like noise.

- **Correction Strategy:**
  - *Coarse Acquisition:* Estimating fractional CFO Δf from the phase difference between the two preamble halves.
  - *Fine Tracking:* Using pilot subcarriers embedded in data symbols to track and correct residual phase rotation symbol-by-symbol.

3.2.2 Implementation: Coarse and Fine Tracking

- Describe adding a CFO term $e^{j2\pi\Delta ft}$ to the time-domain signal.
- Detail the correction blocks: initial de-rotation based on the preamble, followed by the pilot tracking loop during data demodulation.

3.2.3 Analysis: Constellation Stability

- Present "Before" vs. "After" constellation plots.
- **Before:** A spinning circle of points due to uncorrected CFO.
- **After:** A stable, clean constellation locked to the grid.
- Discuss the range of CFO that can be corrected (limited by subcarrier spacing).

Image Placeholder: Constellation with CFO: Spinning vs Corrected
filename: constellation-cfo-tracking.png

Figure 3.2: Constellation with CFO: Spinning vs Corrected

4

Multi-Antenna Systems

4.1 MIMO Theory

4.1.1 Spatial Diversity and Array Gain

- **Spatial Diversity:** Explain that signals arriving at spatially separated antennas fade independently. This reduces the probability that all paths are in a deep fade simultaneously.
- **Array Gain:** Explain that using multiple receive antennas captures more total signal energy, improving the average SNR.
- **Diversity Gain:** Describe how this manifests as a change in the slope of the BER curve (steeper slope = higher diversity order).

4.1.2 Maximum Ratio Combining (MRC)

- Derive or state the optimal MRC combiner rule: $\hat{y} = \frac{\sum h_i^* r_i}{\sum |h_i|^2}$.
- Explain that this weighting scheme maximizes the SNR of the combined signal by favoring stronger antenna branches.

4.2 Implementation: SIMO Architecture

4.2.1 Channel Generation for N_R Antennas

- Describe generating independent Rayleigh fading channel coefficients for each antenna in the 1×2 and 1×4 configurations.

4.2.2 Synchronization Averaging and MRC Equalizer

- Explain the strategy for synchronization in SIMO: calculating Schmidl & Cox metrics and CFO estimates on all antennas independently, then averaging them to improve detection reliability.
- Describe the implementation of the MRC combining rule in the equalizer.

4.3 Analysis: Diversity Gain

4.3.1 Performance Comparison: 1×1, 1×2, 1×4

- Present the combined BER vs. SNR plot for SISO, SIMO 1x2, and SIMO 1x4.
- **Slope Analysis:** Confirm that the 1×2 curve falls much faster (slope ≈ 2) than the 1×1 curve (slope ≈ 1).
- **Array Gain:** Verify the horizontal SNR shift (approx. 3 dB gain for doubling antennas).

Image Placeholder: BER Comparison: SISO vs SIMO (Diversity Slope Analysis)
filename: ber-mimo-diversity.png

Figure 4.1: BER Comparison: SISO vs SIMO (Diversity Slope Analysis)

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Conclusion

5.1 Summary of Achievements

- Recap the successful design and simulation of the complete baseband chain.
- Highlight that the final system is a standard-compliant OFDM link capable of robust operation under multipath fading, timing offsets, and frequency offsets.

5.2 Critical Analysis of Results

- Discuss the trade-offs encountered, such as the computational complexity of Time-Domain estimation vs. its performance gain, or the overhead of pilot subcarriers vs. the ability to track CFO.

5.3 Future Perspectives

- Suggest potential future improvements, such as implementing Spatial Multiplexing (V-BLAST) for higher data rates, adding Forward Error Correction (FEC) coding, or simulating realistic packet-based traffic.

A

Matlab Code