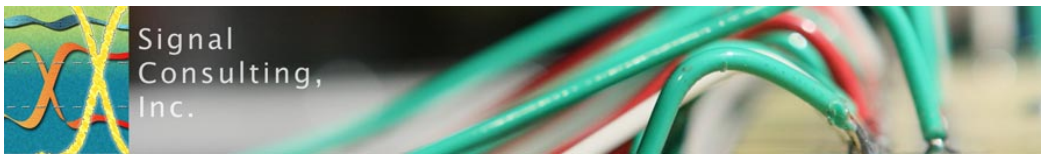


# High-Speed Signal Propagation Seminar

## For Experienced Digital Designers, by Dr. Howard Johnson

About this course | Printable Index

## 1. Time and Frequency

**(Advanced) High-Speed Signal Propagation: Opening Lecture**. *HSSP Seminar* (2015): 1.1-1.4.
[EE BASICS, MANAGEMENT, SERIAL LINK] Delineation of Material to be Covered. Prerequisites. Overview of Program.

(pp. 1-4) Notes
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**Purpose of Simulation**. *HSSP Seminar* (2015): 1.10-1.14.
[MANAGEMENT, SIMULATION] Must We Simulate Everything?. How Advanced Design Really Works. What You'll Need.

(pp. 10-14) Notes
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(7 min.) Movie SD
(7 min.) Movie HD

**Tools for Highly Optimized Work Above 1 GHz**. *HSSP Seminar* (2015): 1.15.
[MANAGEMENT, PROBES, TESTING] Scope and probes. Vector network analyzer. Budget and time for multiple board spins. Ringing and Crosstalk (2D) simulator. Full-wave (3D) simulator. Power integrity simulation.

(page 15) Notes
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**Review of Mathematical Fundamentals**. *HSSP Seminar* (2015): 1.16-1.20.
[BANDWIDTH, EE BASICS, EM FIELDS, RISE TIME] Impedance and Bandwidth. Power Spectral Density of Digital Signal. 3-D Rule of Scaling—Lossless Circuits. 2-D Scaling of PCB Cross-Section.

(pp. 16-20) Notes
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## 2. Lossy Line Parameters

**Transmission Line Basics**. *HSSP Seminar* (2015): 2.1-2.11.
[CHARACTERISTIC IMPEDANCE, TRANSMISSION LINE] Telegrapher's Model. RLGC Model. Meaning of "TEM" mode. Voltage and Current Waveforms on Lossless Line. Charges in Motion (animation). What happens after a Pulse "Leaves the Station?".

(pp. 1-11) Notes
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(37 min.) Movie SD
(37 min.) Movie HD

**Resistive Effects**. *HSSP Seminar* (2015): 2.12-2.30.
[ATTENUATION, SKIN EFFECT, TRANSMISSION LINE] DC Series Resistance. DC Shunt Conductance. How Magnetic Shielding Works. The Walls of a Conductor Form a Shield. Skin Depth vs. Frequency for Copper. The Distribution of Current Changes With Frequency. High-Frequency Current Flows Only in a Shallow Band of Effective Depth d. High-Frequency Magnetic Fields. Paradox: Two Round, Symmetric Conductors. Proximity Effect. Popsicle-Stick Analysis. Proximity Effect for Differential Pcb Traces. Surface Roughness. Onset of Roughness Effect. Complete Resistance Model.

(pp. 12-30) Notes
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(39 min.) Movie SD
(39 min.) Movie HD

**Dielectric Effects**. *HSSP Seminar* (2015): 2.31-2.37.
[ATTENUATION, DELAY, TRANSMISSION LINE] Microwaves Heat All Insulating Materials. Measurement of Dielectric Loss. Conduction Current and Displacement Current. Deterioration in Dielectric Constant. Complete Capacitance Model. Approximate Rule of Dielectric Mixtures.

(pp. 31-37) Notes
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(17 min.) Movie SD
(17 min.) Movie HD

## 3. Performance Regions

**TEM Transmission Media**. *HSSP Seminar* (2015): 3.1-3.7.
[DISPERSION, NON-TEM, TRANSMISSION LINE] Attenuation vs. Frequency (graph). Characteristic Impedance (graph). Approach to Modeling. General Properties. Is a Transmission Line Ever Not a Transmission Line? (demonstration).

(pp. 1-7) Notes
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**Lumped-Element Behavior**. *HSSP Seminar* (2015): 3.8-

(pp. 8-14) Notes

3.14.
[CAPACITANCE, INDUCTANCE, REFLECTIONS] Lumped-Element Modeling. Limits to Lumped-Element Analysis. Pi-Model for LC mode. Pi-Model Special Cases. Reflection Coefficients for Reactive Loads. Reflection From Capacitive Load (Derivation).

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(10 min.) Movie SD
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**RC Region**. *HSSP Seminar* (2015): 3.15-3.20.
[ATTENUATION, RESISTANCE, TRANSMISSION LINE] Elmore Delay Estimation. Elmore Delay for Cascade of RC Networks. On-chip: Long-Haul Distribution.

(pp. 15-20) Notes
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(6 min.) Movie SD
(6 min.) Movie HD

**Skin-Effect Region**. *HSSP Seminar* (2015): 3.21-3.25.
[ATTENUATION, SKIN EFFECT, TRANSMISSION LINE] Random Test Patterns. Effective Settling Time. Pretty-Bad Test Pattern.

(pp. 21-25) Notes
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(12 min.) Movie SD
(12 min.) Movie HD

**Dielectric-Loss-Limited Region**. *HSSP Seminar* (2015): 3.26-3.27.
[ATTENUATION, DIELECTRIC LOSS, TRANSMISSION LINE] Slope of loss versus frequency. Implication for speed and distance scaling.

(pp. 26-27) Notes
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(3 min.) Movie SD
(3 min.) Movie HD

**Measuring Characteristic Impedance**. *HSSP Seminar* (2015): 3.28-3.31.
[CHARACTERISTIC IMPEDANCE, TESTING, TRANSMISSION LINE] Influence of Losses on TDR Measurement.

(pp. 28-31) Notes
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(9 min.) Movie SD
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**Onset of Non-TEM Behavior**. *HSSP Seminar* (2015): 3.32-3.33.
[DISPERSION, EXAMPLES, NON-TEM, TRANSMISSION LINE] Equations for Estimating.

(pp. 32-33) Notes
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**Non-TEM Mode Example**. *HSSP Seminar* (2015): 3.34-3.35.
[DISPERSION, EXAMPLES, NON-TEM, TRANSMISSION LINE] Comparing skin-effect, dielectic, and non-TEM dispersion effects.

(pp. 34-35) Notes
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**Equalizers**. *HSSP Seminar* (2015): 3.36-3.49.
[EQUALIZATION, EXAMPLES] PCB Trace Performance (graph). Received Signal at End of Line (waveform). Criteria for ISI Errors. ISI Criteria in the Frequency Domain. TTL/CMOS Levels Have Little ISI Tolerance. ISI Tolerance of Signaling Schemes. Time-Domain Response with 1st-Order Digital Equalizer. Digital Transmit Pre-emphasis Analysis. Effect of Equalization (1-m).

(pp. 36-49) Notes
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(35 min.) Movie HD

Effect of Equalization (0.5-m). Digital EQ Eye Patterns for 10BASE-T Ethernet. Real backplanes. 4-Tap Transmit-Based Equalizer for PAM-4.

**Analog Equalizer Examples**. *HSSP Seminar* (2015): 3.50-3.54.
[EQUALIZATION, EXAMPLES] Analog 1-Pole Equalization Circuit. Refinement for Constant-Impedance Input. Symmetric Equalizer. Balanced, Constant-Impedance Symmetric Equalizer.

(pp. 50-54) Notes
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**Digital Receive-Based Equalization**. *HSSP Seminar* (2015): 3.55-3.56.
[EQUALIZATION] Decision Feedback Equalizer.

(pp. 55-56) Notes
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## 4. Frequency-Domain Modeling

**Frequency-Domain Analysis**. *HSSP Seminar* (2015): 4.1-4.9.
[S-PARAMETERS] Why bother with the frequency domain?. Terminology of Frequency-Domain Analysis. Sine In, Sine Out. The advantage of LTI modeling. Information Necessary to Characterize an LTI System. Is a Digital Driver LTI?. Frequency-Based Analysis.

(pp. 1-9) Notes
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**Scattering parameters (S-parameters)**. *HSSP Seminar* (2015): 4.10-4.20.
[S-PARAMETERS] S-Parameter Test Setup. Wafer Probe Design. Transmission Lines are Symmetric. Do Not Cascade S21 Terms. Do Not Multiply S-Matrices. Proper S-Matrix Combination. Conversions Between Forms. Using S-Parameters with Spice. Good Applications for S-Parameters.

(pp. 10-20) Notes
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**Linear System Theory (Supplemental)**. *HSSP Seminar* (2015): 4.21-4.28.
[S-PARAMETERS] Theory of Linearity. Theory of Linear Superposition. Theory of Time-Invariance. Convolution. Comparison of Time- and Frequency-Domain Approaches.

(pp. 21-28) Notes
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## 5. PCB Traces And Connectors

**Design Examples**. *HSSP Seminar* (2015): 5.1-5.15.

(pp. 1-15) Notes

[ATTENUATION, EXAMPLES, MICROSTRIP, STRIPLINE] Microstrip Examples. Stripline Examples. Resistive Loss Versus Trace Width. Nickel Plating. Passivation and Soldermask. Effect of Thin Soldermask Coating. Form of Specification for Laminates. Laminate Examples. How Far Can I Go?. Example: PCI Express 2.5 Gb/s. Example: RocketIO at 6.25 Gb/s.

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(25 min.) Movie SD
(25 min.) Movie HD

**Potholes (Transmission Line Imperfections)**. *HSSP Seminar* (2015): 5.16-5.25.
[CAPACITANCE, INDUCTANCE, REFLECTIONS, TRANSMISSION LINE] Reflection from a Capacitor. Reflection from a Short Hi-Z Segment. Compensation Idea. Example: Compensated Capacitance. Design Goal: Balance L and C. Limits to Applicability.

(pp. 16-25) Notes
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**PCB Connectors**. *HSSP Seminar* (2015): 5.26-5.41.
[CONNECTORS, CROSSTALK, EMC, REFLECTIONS] Measuring Signal Fidelity. Measuring Crosstalk. Measuring Ground-Transfer Impedance (EMI). Examples of Backplane Connectors. ERmetZD, I-Trac. RF Connectors. Concept of Tapered Transitions. Practical Co-planar Waveguide Taper. Nearly Co-planar Waveguide (NPW) Taper. Simple Taper Example. RF Connector Sizes. RF Connector Comparison.

(pp. 26-41) Notes
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(28 min.) Movie SD
(28 min.) Movie HD

**Connecting layers**. *HSSP Seminar* (2015): 5.42-5.43.
[CROSSTALK, REFLECTIONS, VIAS] How Vias Behave as Connectors.

(pp. 42-43) Notes
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(5 min.) Movie SD
(5 min.) Movie HD

**Inductance of PCB Via**. *HSSP Seminar* (2015): 5.44-5.51.
[EXAMPLES, INDUCTANCE, SILAB HSSP, VIAS] Conditions of Measurement. Path of Return Current. Measuring Incremental Parameters. Four-Terminal Inductance Measurement. Step-Response Measurement of Inductance. Measured Data. Impedance of a Via.

(pp. 44-51) Notes
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(32 min.) Movie SD
(32 min.) Movie HD

**Via Geometry**. *HSSP Seminar* (2015): 5.52-5.63.
[CHARACTERISTIC IMPEDANCE, LAYOUT, VIAS] Movie Quiz: Adjustments to Via Geometry. Shallow Blind Vias. Blind Via Capacitance (table). Inductance of Vias That Penetrate Multiple Planes. Via Inductance (example calculation). Stripping Via Pads on Unused Layers. Efficacy of Stripping Pads.

(pp. 52-63) Notes
(.pptx) Source
(26 min.) Movie SD
(26 min.) Movie HD

**Dangling Vias**. *HSSP Seminar* (2015): 5.64-5.73.
[LAYOUT, REFLECTIONS, VIAS] Effect on Circuit Performance. Ways to Truncate Dangling Vias. Efficacy of Counter Boring.

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Wine-Glass Via. Oval Clearances. Differential Via with Oval Clearance. Differential Via with Extra Ground Vias.

(31 min.) Movie SD
(31 min.) Movie HD

## 6. Differential Signaling

**Purpose of Differential Signaling**. *HSSP Seminar* (2015): 6.1-6.11.
[DIFFERENTIAL SIGNALING, EE BASICS] Defeating Ground Bounce. Comparison of UTP and PCB Differential Applications. Differential Geometry on PCB. Distribution of Current in Edge-Coupled Microstrip. Differential Vocabulary. Modes of Propagation. Effect of Asymmetry. Vocabulary: Differential Peak-to-Peak Voltage.

(pp. 1-11) Notes
(.pptx) Source
(30 min.) Movie SD
(30 min.) Movie HD

**Differential Microstrip Geometry**. *HSSP Seminar* (2015): 6.12.
[DIFFERENTIAL SIGNALING, LAYOUT, MICROSTRIP] Trade-offs Between Separation and Trace Width.

(page 12) Notes
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**Differential Stripline Geometry**. *HSSP Seminar* (2015): 6.13-6.14.
[DIFFERENTIAL SIGNALING, LAYOUT, STRIPLINE] Also - Offset Stripline Geometry.

(pp. 13-14) Notes
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(2 min.) Movie SD
(2 min.) Movie HD

**Diffrential Broadside-Coupled Geometry**. *HSSP Seminar* (2015): 6.15-6.17.
[BROAD-SIDE COUPLING, DIFFERENTIAL SIGNALING] Asymmetry in Broadside Configuration.

(pp. 15-17) Notes
(.pptx) Source
(6 min.) Movie SD
(6 min.) Movie HD

**Trace Width vs. Distance**. *HSSP Seminar* (2015): 6.18-6.19.
[ATTENUATION, LAYOUT, TRANSMISSION LINE] Summary of trace width effects.

(pp. 18-19) Notes
(.pptx) Source
(2 min.) Movie SD
(2 min.) Movie HD

**Differential Receivers Tolerate High-Frequency Losses**. *HSSP Seminar* (2015): 6.22.
[ATTENUATION, DIFFERENTIAL SIGNALING] Effect of Receiver Thresholds on Signal Quality in the Face of Signal Dispersion.

(page 22) Notes
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(3 min.) Movie SD
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**Matching to an External Cable**. *HSSP Seminar* (2015):

(page 23) Notes

6.23.
[DIFFERENTIAL SIGNALING, EMC, EXAMPLES] Example of Well-Balanced Interface.

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(3 min.) Movie SD
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**Reducing EMI with Differential Signaling**. *HSSP Seminar* (2015): 6.24-6.25.
[DIFFERENTIAL SIGNALING, EMC, EXAMPLES] Analysis of When Tight Trace Spacing Might Affect Signal Radiation.

(pp. 24-25) Notes
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**Visualizing Differential Crosstalk**. *HSSP Seminar* (2015): 6.26-6.30.
[CROSSTALK, DIFFERENTIAL SIGNALING, EXAMPLES, STRIPLINE] Tight Coupling vs. Crosstalk.

(pp. 26-30) Notes
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(7 min.) Movie SD
(7 min.) Movie HD

**Breaking Up a Pair**. *HSSP Seminar* (2015): 6.32-6.33.
[LAYOUT, REFLECTIONS, TRANSMISSION LINE] Excess Inductance Method of Analysis.

(pp. 32-33) Notes
(.pptx) Source
(6 min.) Movie SD
(6 min.) Movie HD

**Differential Termination**. *HSSP Seminar* (2015): 6.34-6.35.
[CIRCUIT TOPOLOGY, DIFFERENTIAL SIGNALING, TERMINATION] Common and Differential Modes of Termination. Achieving Both.

(pp. 34-35) Notes
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(2 min.) Movie SD
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**Changing Reference Planes**. *HSSP Seminar* (2015): 6.36-6.38.
[LAYER STACK, REFERENCE PLANES] Differential U-Turn. Purpose of Ground Connections Between the Planes.

(pp. 36-38) Notes
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(9 min.) Movie SD
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**Managing Trace Skew**. *HSSP Seminar* (2015): 6.39-6.40.
[SKEW] Analysis of Skew Magnitude. Effect of Circuit Floorplanning.

(pp. 39-40) Notes
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(5 min.) Movie HD

**Locating Reflections**. *HSSP Seminar* (2015): 6.41-6.48.
[PROBES, TESTING] Probe technique.

(pp. 41-48) Notes
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**Value of DC blocking capacitor**. *HSSP Seminar* (2015): 6.50-6.53.
[DC BLOCK] Modeling DC baseline wander. Maximum wander

(pp. 50-53) Notes
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varies with data coding.

**DC Blocking Capacitor Layout**. *HSSP Seminar* (2015): 6.54-6.55.
[DC BLOCK, LAYOUT] General procedure for optimizing the layout.

(pp. 54-55) Notes
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**DC Blocking Capacitor Reflections**. *HSSP Seminar* (2015): 6.56-6.57.
[DC BLOCK, REFLECTIONS] Method of analysis. Example values.

(pp. 56-57) Notes
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**DC Blocking Capacitor Resonance**. *HSSP Seminar* (2015): 6.58-6.61.
[DC BLOCK, LAYOUT] Tuning the cap value doesn't help.

(pp. 58-61) Notes
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**Differential S-Parameters**. *HSSP Seminar* (2015): 6.62-6.64.
[DIFFERENTIAL SIGNALING, S-PARAMETERS] Practical advice.

(pp. 62-64) Notes
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## 7. through 11. Transmission Media

**Transmission Media**. *HSSP Book* (2003): Chap 7-11.
[TRANSMISSION LINE] Chapters 7-11 from the book *High-Speed Signal Propagation: Advanced Black Magic* were not filmed. These chapters dealt with specific transmission media, such as generic building cabling standards, 100-ohm twisted-pair cabling, 150-ohm STP-A cable, coaxial cable, and fiber-optic cable.

(pp. 439-578) Book

## 12. Clock Distribution And Jitter

**Routing Clocks and Other High-Speed Signals**. *HSSP Seminar* (2015): 12.1-12.14.
[CLOCKS, LAYOUT] Special Requirements for Clock. Clock Repeaters are Built to Provide Multiple Low-Skew Clocks. Active Skew Correction. Clock Tree. Zero-Delay Clock Repeater. Point to Remember. Stripline vs. Microstrip Delay. Delay of Typical Microstrips. Importance of Terminating Clock Lines. Ringing on Short, Un-terminated Trace Distorts Timing. Ground Bounce Effect on Clock. Crosstalk. Advice on Routing Differential Clocks.

(pp. 1-14) Notes
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(23 min.) Movie SD
(23 min.) Movie HD

**Serpentine Traces**. *HSSP Seminar* (2015): 12.15-12.19.
[CLOCKS, DELAY, LAYOUT] Serpentine Coupling. Coupled Serpentine Waveforms. 24-Section Serpentine. Rules for Successful Delay Lines.

(pp. 15-19) Notes
(.pptx) Source
(13 min.) Movie SD
(13 min.) Movie HD

**Hairball Networks**. *HSSP Seminar* (2015): 12.20-12.34.
[MULTI DROP] To Tee or Not To Tee. Basic Tee with No Termination. Add Receivers (and ESD Diodes). Tee with Slow Driver. Tee with Both-Ends Termination. Tee with Weak End Termination. Tee with Sneaky Impedance Adjustment. Tee with Series Termination. Unbalanced Tee with Series Termination. Unbalanced Tee with End Termination. Unbalanced Tee with Distributed Damping. Apply Your Knowledge: Check the "H" For Resonance..

(pp. 20-34) Notes
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(27 min.) Movie HD

**Daisy-Chain Distribution**. *HSSP Seminar* (2015): 12.35-12.45.
[MULTI DROP] Example: Reflection Amplitude in Daisy Chain. Reflection Coefficient. Reducing the Impact of Tap Capacitance. Daisy-Chain Case Study. Using Five Loads of 3 pF Each. Squeeze Loads Closer Together. Why Overshoot Occurs. Change End Termination to 36 Ohms. Rules for Good Daisy-Chaining. Ironing Out the Bumps (2-in. Spacing).

(pp. 35-45) Notes
(.pptx) Source
(24 min.) Movie SD
(24 min.) Movie HD

**Frequency Offset, Wander, and Jitter**. *HSSP Seminar* (2015): 12.46-12.59.
[CLOCKS, JITTER] Clock Recovery on a Serial Link. Clock Specifications. Why Are Oscillators Imperfect?. Effect of Frequency Offset in PLL Clock Recovery Circuit. Effect of Wander in PLL Clock Recovery Circuit. Racing Game Analogy for Understanding Tracking and Filtering Behavior. Your Tracking Filter. Decomposition of Trajectory. What's Better?. Car vs. PLL. Tracking Gain vs. Frequency. Effect of Resonance on Cascaded Systems. Effect of Large Multiplication Ratio. SONET Clock Architecture.

(pp. 46-59) Notes
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(35 min.) Movie SD
(35 min.) Movie HD

**Jitter Specifications**. *HSSP Seminar* (2015): 12.60-12.74.
[JITTER, TESTING] Appearance of Jitter. Jitter Histogram. Decomposition of Jitter Histogram. Extrapolation of Random Jitter. Deterministic vs. Random Jitter. Extra for Experts: Jitter Measurement Techniques. Measuring Deterministic Jitter. Measuring Random Jitter. Combining Deterministic and Random Jitter. Fudge Factors for Random Gaussian Jitter. Time-Interval Analysis (TIA). Golden-PLL Method for Measuring Jitter. BERT Scan. Spectral Measurement of Jitter Variance.

(pp. 60-74) Notes
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(19 min.) Movie SD
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**Words of Wisdom**. *HSSP Seminar* (2015): 12.75.
[MANAGEMENT] Measure everything. Sit with your layout people. Make your hardware testable.

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## HSSP Seminar—Extra Material

**Serial Link Architecture**. *HSSP Seminar* (2015). [CROSSTALK, DIFFERENTIAL SIGNALING, EXAMPLES, LAYOUT, SILAB HSSP] Example of 10Gbps Serial Link. Introduction to System Modelling. Trace Layout. Crosstalk from Various Sources.

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**Serial Link Budgeting**. *HSSP Seminar* (2015). [ATTENUATION, BACK PLANE, DIFFERENTIAL SIGNALING, DISPERSION, EXAMPLES, REFLECTIONS, SILAB HSSP] A Simple Signal Quality Budget. Discussion of PCB Transitions. Backdrilling. PCB Trace Losses. Signal Dispersion and the Effect of Equalization.

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# About This Course

*Advanced High-Speed Signal Propagation* is an advanced-level course for experienced digital designers who want to press their designs to the upper limits of speed and distance. Focusing on lossy transmission environments like backplanes, cables and long on-chip interconnections, this two-day course teaches a unified theory of transmission impairments that apply to any transmission media. This course is an advanced sequel to the *High-Speed Digital Design Seminar*.

## Main Topics

| | | | |
|---|---|---|---|
| serial link | skin effect | dielectric loss | dispersion |
| equalization | jitter | differential signaling | S-parameters |
| DC block | data coding | vias | |

## Who should watch this course?

- Digital logic designers
- System architects
- Chip designers
- Applications engineers
- Anyone who works with digital logic at speeds in excess of 1GHz

This is a practical course. It is filled with practical examples and explanations.

A basic understanding of transmission-line reflections and ringing is assumed. Delegates without the benefit of formal training in analog circuit theory can use and apply the formulas and examples from this course, however, delegates who have completed (at least) a first-year class in introductory linear circuit theory will comprehend the material at a deeper level. The author assumes you are familiar with the following concepts from the High-Speed Digital Design Seminar: transmission lines (basic TEM mode), transmission line reflections, terminations, and simple R, L, C circuits.

For further study after you have seen the video course, the author reccomends that you purchase his book, *High-Speed Signal Propagation: Advanced Black Magic*. The book, being 776 pages in length, obviously delves into the subject matter in greater detail. Think of the seminar as an introduction and, if you like it, get the book for on-the-job reference. The book includes extra chapters on coaxial cable, twisted-pair cable, ribbon cable and fiber-optics that did not fit in the seminar.

Go to the course | Show me the book

## How to view this course

The author recommends that you view no more than one hour at a time. It may help for you to print out the notes pages for each lecture and take written notes. The sections in the notes marked *Points to Remember* are not often highlighted in the lecture, but offer good opportunities for personal thought and reflection.

The three courses provide a certain degree of redundancy. Each begins with a section designed to make each attendee aware of certain basic concepts and vocabulary peculiar to that course. Where there is overlap, the author emphasizes different aspects of the core material, uses different examples, and approaches the subjects from varying angles. He recommends that you watch all three courses, all the way through, including all the extra movies.

The course materials cover much more material than could possibly be presented in the six days of lecture that we were able to film. Dr. Johnson arranged the slides with extra material to give himself the flexibility to focus on specific issues of interest to each particular class and to respond to questions. We include the full set of student materials here for your reference, even though some of those slides were not filmed. To help you keep on track, slide numbers appear on the right side of the course contents listing.

In addition to the student course materials, the collection includes a full set of instructor materials in Powerpoint format. The instructor materials include original source artwork that may be of interest to those attempting to teach these courses. The necessary animation files, should you wish to use them independant of the lectures, are also available.

Go to the course | Get the animations