Characterization of a Very Shallow Water Acoustic Communication Channel

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Why Do Channel Estimation?

- Relatively few papers have focused on the fundamental process of characterizing the underwater acoustic channel
- There is no typical underwater channel
- Is a necessary step for the design of a successful communication system
- Numerous channel measurements are required to build up a database of underwater environments for more realistic network simulations

Field Test Details

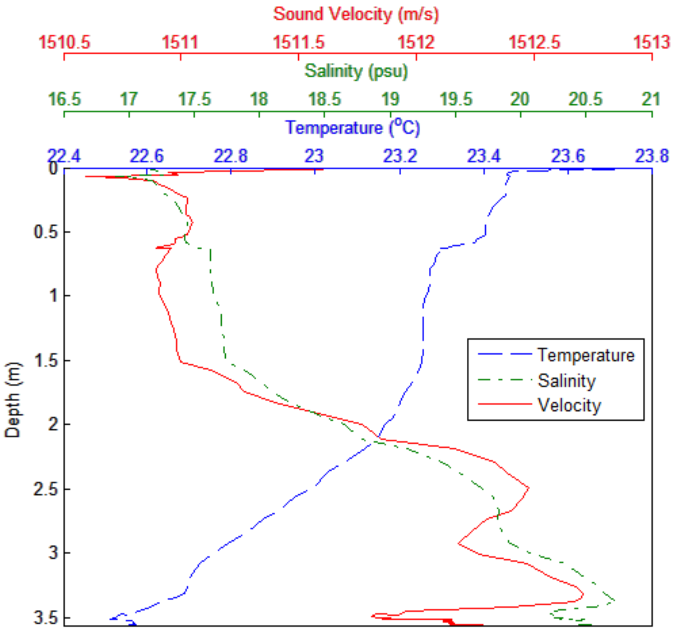
- Location: Hudson River estuary
- Date: August 21, 2008
- Depth: 3 m
- Distances: 200 m and 505 m
- Associated Equipment:
  - NI USB-6221 DAQ for transmitting (200 ksamples/sec)
  - NI PCI-6123 DAQ for recording (200 ksamples/sec)
  - ITC-6050C hydrophones, custom emitter
- Signals
  - Comb signal containing 5 sinusoidal components – 35, 45, 60, 75, and 85 kHz – for 1 minute
  - 50-ms linear frequency modulated (LFM) chirp signal spanning 20-100 kHz, repeated for 30 seconds

Sound Velocity Profile

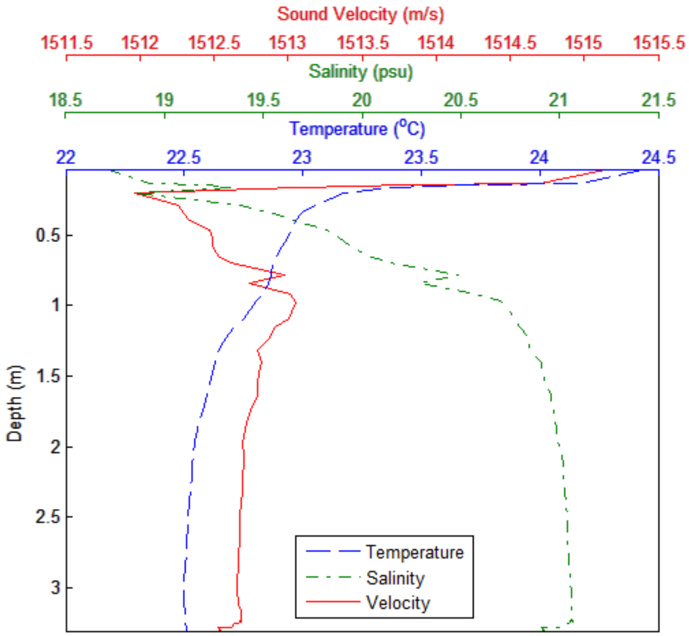
Medwin's expression:

$$c = 1449.2 + 4.6T - 5.5 \times 10^{-2}T^2 + 2.9 \times 10^{-4}T^3 + (1.34 - 10^{-2}T)(S - 35) + 1.6 \times 10^{-2}D$$

Limits:
$0 \leq T \leq 35$°C
$0 \leq S \leq 45$ psu
$0 \leq D \leq 1000$ m



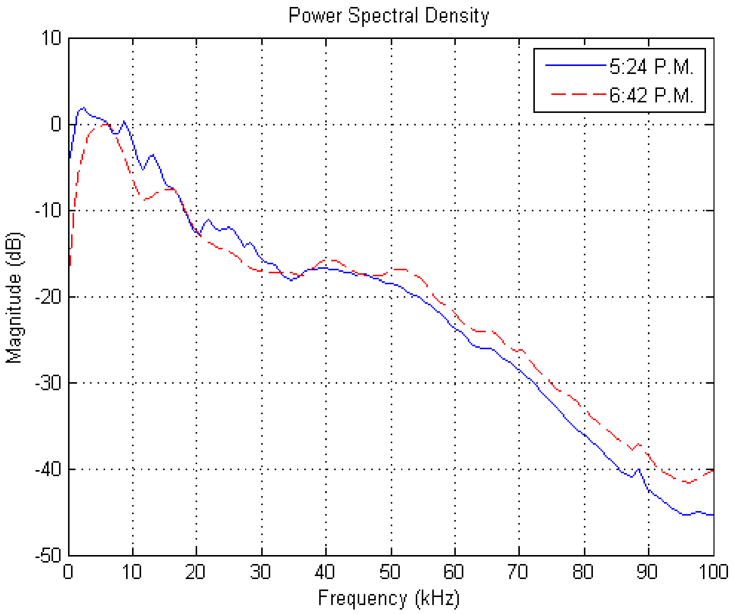
Sound velocity profile for 505-meter channel



Sound velocity profile for 200-meter channel

Ambient Noise

- Recorded for 30 seconds before emitting test signals
- Power spectral density (PSD) of noise was estimated via a conventional periodogram technique based on a 256-point FFT together with a Hanning window and no overlap

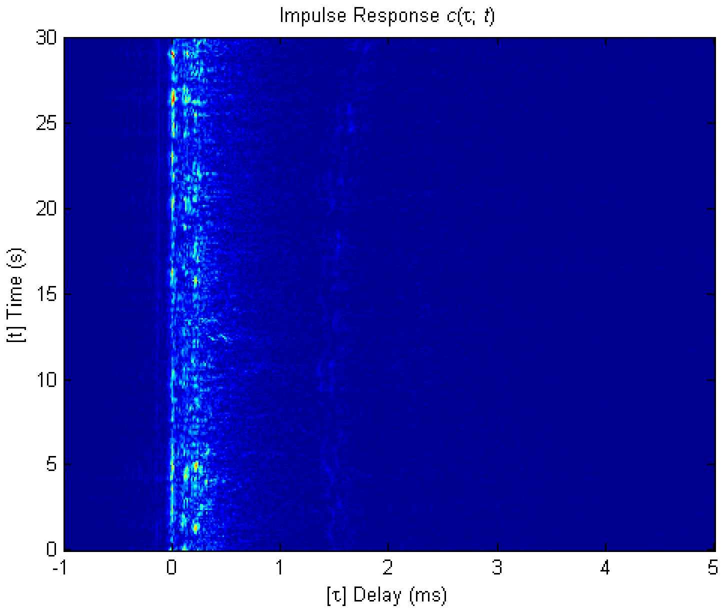


PSD of ambient noise in Hudson River estuary

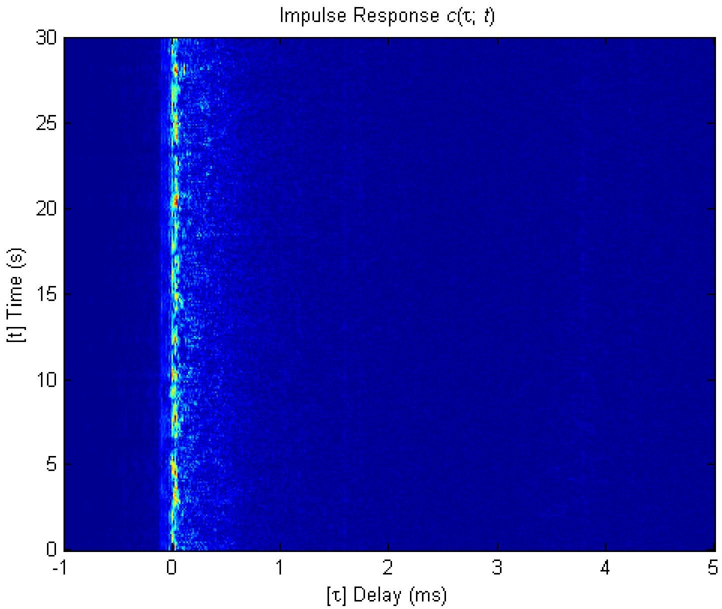
Time-Variant Impulse Response

- Using the wide-sense stationary uncorrelated scattering (WSSUS) channel model,
  - The 50-ms chirp signals were recorded 1 meter from the emitter and either 200 or 505 meters away (depending on the test)
  - The received signal and 1-meter reference signal were run through a 10th order high-pass Butterworth filter at 20 kHz to eliminate out-of-band noise
  - One chirp was extracted from the 1-meter reference signal, accurate to the sample
  - The imaginary part of the reference chirp signal was obtained via the Hilbert transform
  - The received signal was cross-correlated with the complex conjugate of the reference chirp signal

Time-Variant Impulse Response



Successive time-variant impulse response estimates at 505m

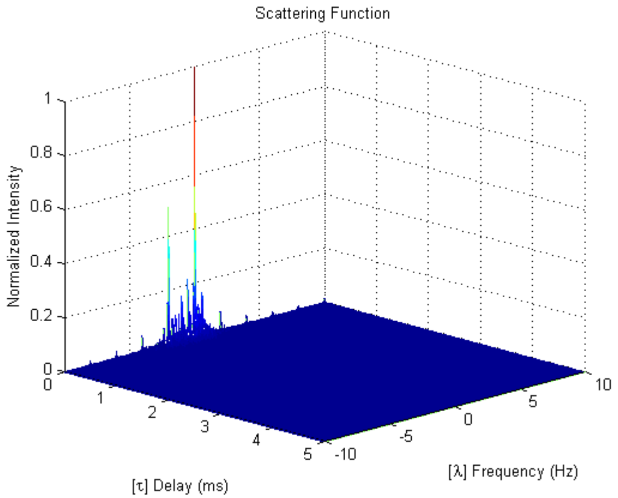


Successive time-variant impulse response estimates at 200m

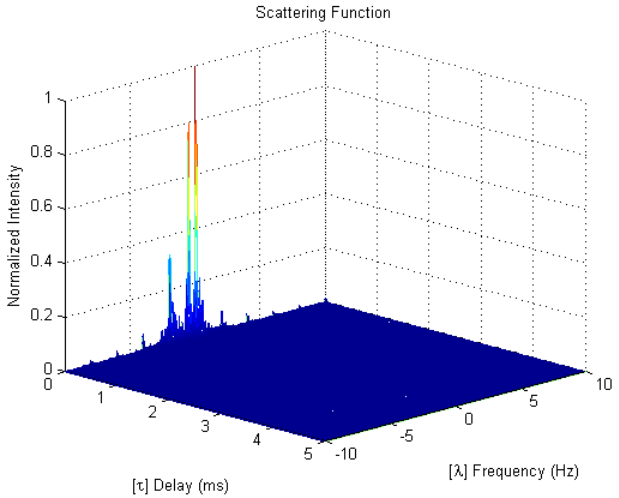
Scattering Function

- Gives the average power output of the channel as a function of time delay τ and Doppler frequency λ
- Is the basis for computing the remainder of the channel characterization functions

$$S_c(\tau;\ \lambda) = \int_{-\infty}^{\infty} A_c(\tau;\ \Delta t)\, e^{-j2\pi\lambda\Delta t}\, d\Delta t$$



Scattering function at 505m



Scattering function at 200m

Multipath Intensity Profile

- *P*(*τ*) gives the average power output as a function of time delay *τ*
- Computed by summing the power levels over the *λ* values

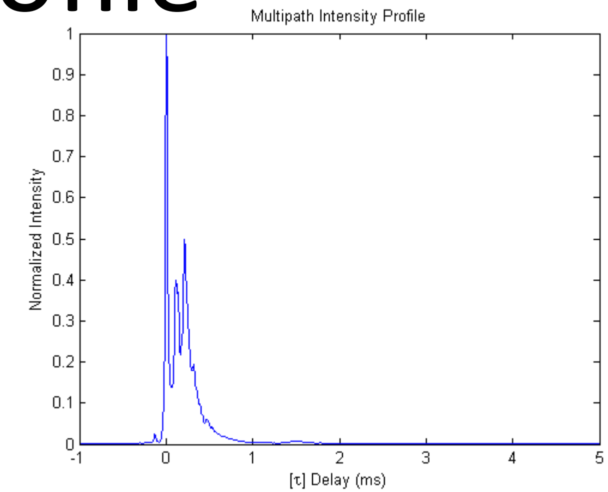
$$P(\tau) = \int S_c(\tau;\, \lambda)d\lambda$$

Doppler Shift and Spread (Hz) of Strong Multipath Arrivals

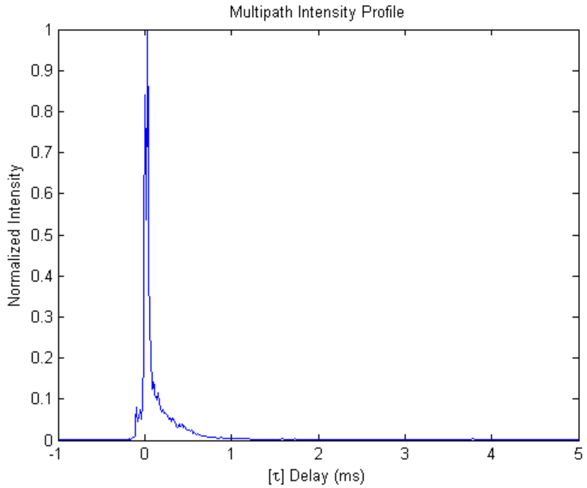
	200m			505m		
	Time (ms)	Shift	Spread	Time (ms)	Shift	Spread
Arrival 1	0.010	-0.5029	2.0677	0.010	-0.7279	2.0831
Arrival 2	–	–	–	0.115	-0.6689	2.2931
Arrival 3	–	–	–	0.215	-0.7336	2.4141

Delay Spread of Multipath Intensity Profile (ms)

	Mean Excess Delay	RMS Delay Spread	Maximum Excess Delay
200m	0.1002	0.1490	0.1850
505m	0.1835	0.1625	0.4000



Multipath intensity profile at 505m



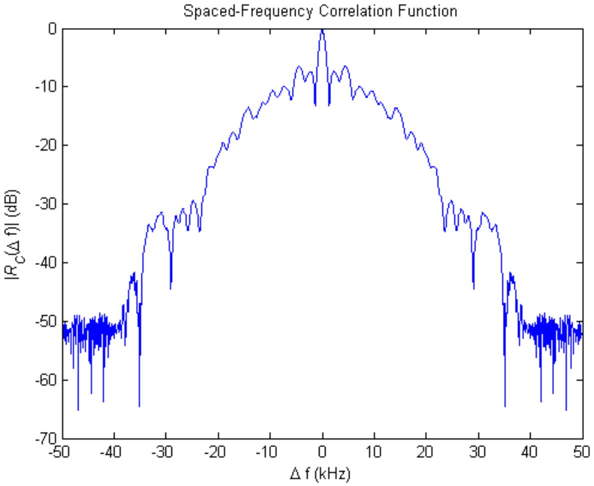
Multipath intensity profile at 200m

Spaced-Frequency Correlation Function

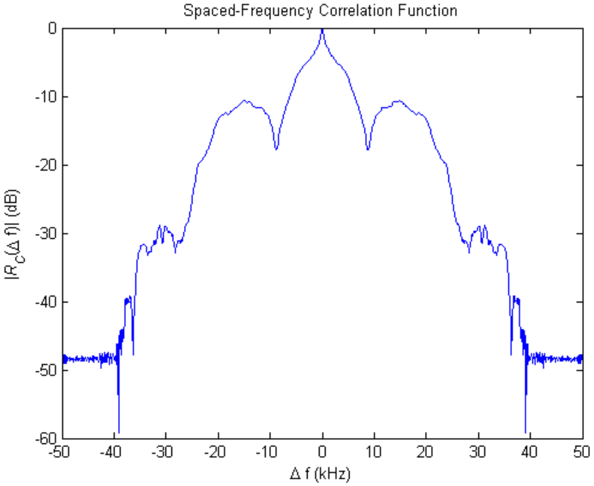
- Fourier transform of the MIP
- Indicates the coherence bandwidth of the channel, a statistical measure of the range of frequencies over which the channel passes all spectral components with approximately equal gain and linear phase

Coherence Bandwidth (Hz)

	-3 dB	-6 dB	-10 dB
200m	2165	7993	12323
505m	1166	1665	2165



Spaced-frequency correlation function at 505m



Spaced-frequency correlation function at 200m

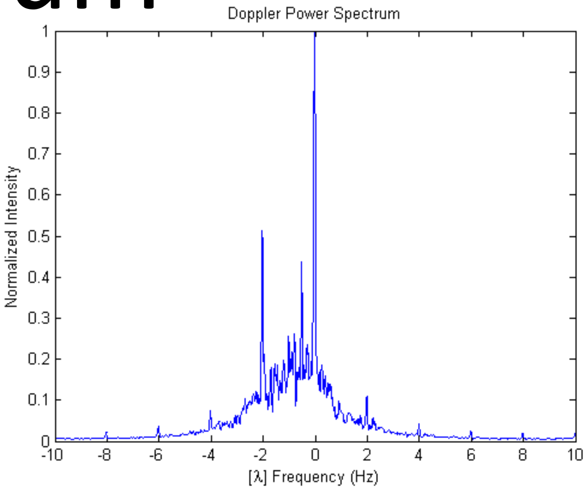
Doppler Power Spectrum

- Provides the signal intensity as a function of the Doppler frequency λ
- Computed by summing the power of spectral components of the scattering function over the time delay τ

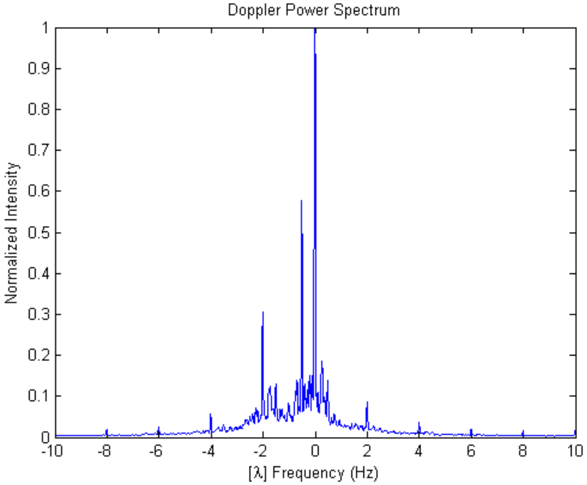
$$P(\lambda) = \int S_c(\tau; \lambda) d\tau$$

Overall Doppler Shift and Spread (Hz)

	Shift	Spread
200m	-0.4806	2.9408
505m	-0.6237	2.8177



Doppler power spectrum at 505m



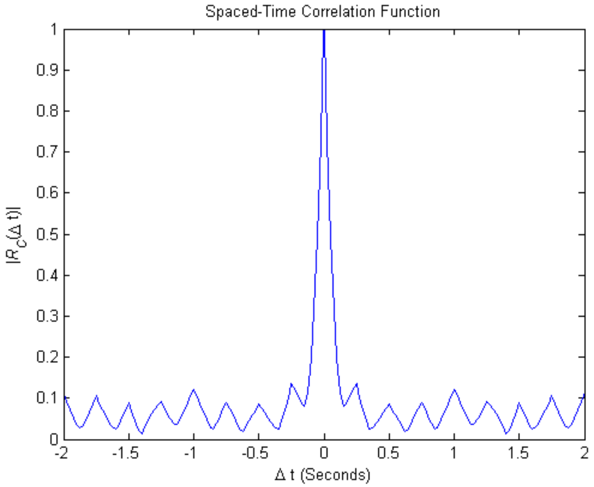
Doppler power spectrum at 200m

Spaced-Time Correlation Function

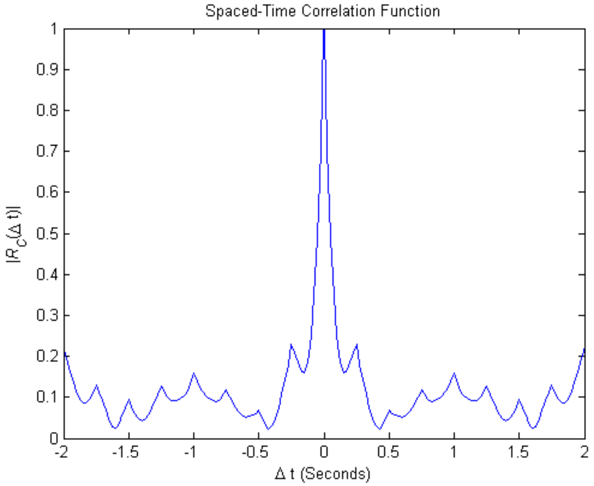
- Fourier transform of the Doppler power spectrum
- Provides the channel's coherence time, a measure of the expected time duration over which the channel's response is essentially invariant

Coherence Time (ms)

	0.5 (-3dB)	0.25 (-6dB)	0.1 (-10 dB)
200m	50	150	650
505m	50	150	250

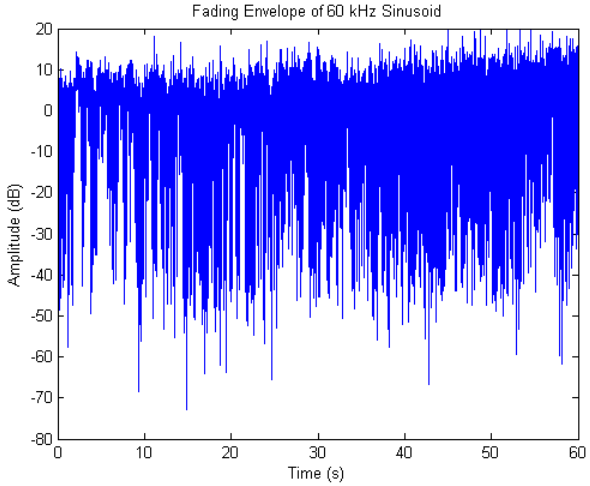


Spaced-time correlation function at 505m

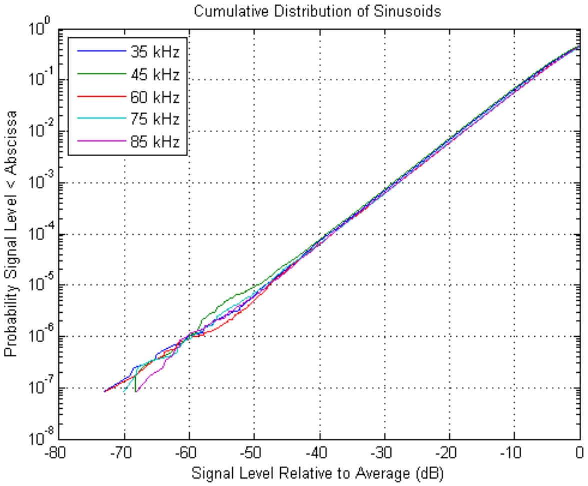


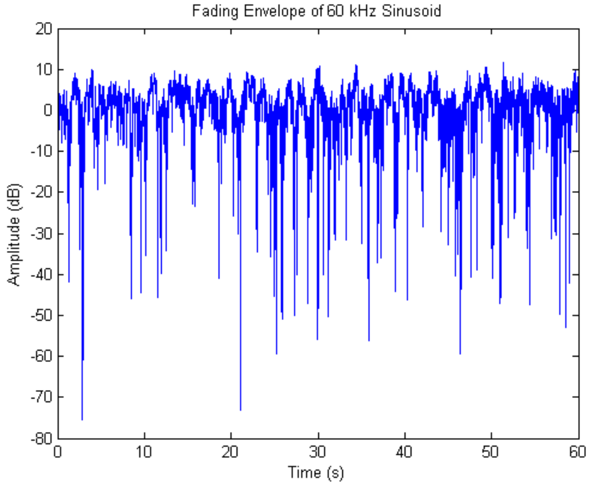
Spaced-time correlation function at 200m

Fading Characteristics

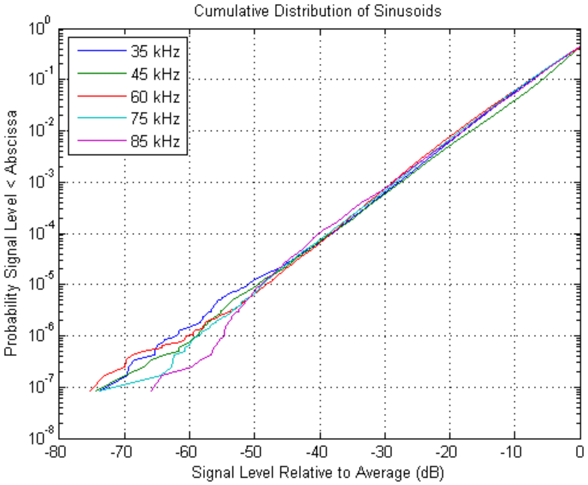


505m





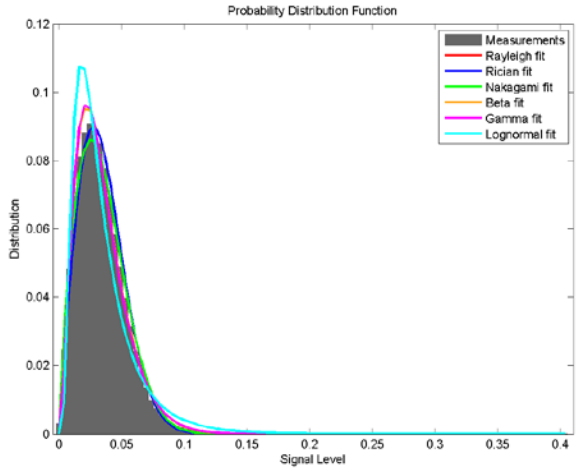
200m



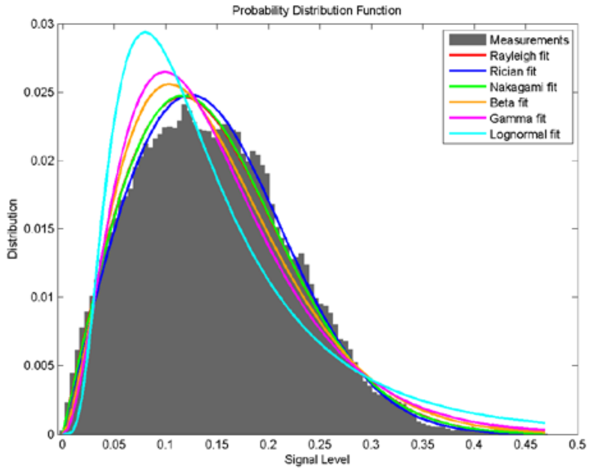
Distribution Fitting

- Maximum likelihood estimation was used to fit the data to the Rayleigh, Rice, and Nakagami-*m* (as well as other less likely) distributions
- Goodness of fit was tested with three different metrics – Kullback-Leibler divergence, Bhattacharyya distance, and a metric based on the Bhattacharyya coefficient (Comaniciu, Ramesh, and Meer)
- 200m => Ricean fading
- 505m => Nakagami-m fading

  (m ≈ 0.89, worse than Rayleigh fading)



PDF of measurements and fits at 505m



PDF of measurements and fits at 200m

Implications for Communication

- (Time domain) If $T_m > T_s$, the channel exhibits frequency-selective fading, which results in channel-induced ISI
  - At 200m, $T_m = 0.1850$ ms => 5400 symbols per second
  - At 505m, $T_m = 0.4000$ ms => 2500 symbols per second
- (Frequency domain) If $W > f$, where W is the bandwidth required for modulation and f is the coherence bandwidth, the channel imposes frequency-selective degradation
- (Time domain) If $T_c > T_s$, the channel exhibits slow fading
  - In the Hudson, the -3dB coherence time is 50ms, which is most likely significantly longer than T_s => slow fading channel
- (Frequency domain) If $W > f_d$, the channel is referred to as slow fading
- Harsh condition over long links => deploy multi-hop network

Summary

- LFM chirp signals and a comb signal were emitted during the experiment
- Environmental conditions were recorded
- Impulse response estimates were used to derive channel characterization functions
- Various distributions were fitted to amplitude fluctuations

Acknowledgments

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