Underwater Wireless Communications: Challenges and Progress

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- The opinions expressed in this presentation represent my own and not those of my funding agencies.

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Why Underwater Wireless?

Water covers >70% of Earth Surface …

but how much do we know about oceans?

Ocean Monitoring and Exploration:

Neptune Project

Underwater Wireless Communications

- Applications:
  - Unmanned Underwater Vehicles (UUV)
  - Divers, Robots, and Floating Sensors
- Possible communication means:
  - Optical beams
  - Radio Frequency (RF) Waves
  - Sound Propagation:

    Short range (<1 km): 100 kHz

    Medium range (1-10 km): 40 kHz

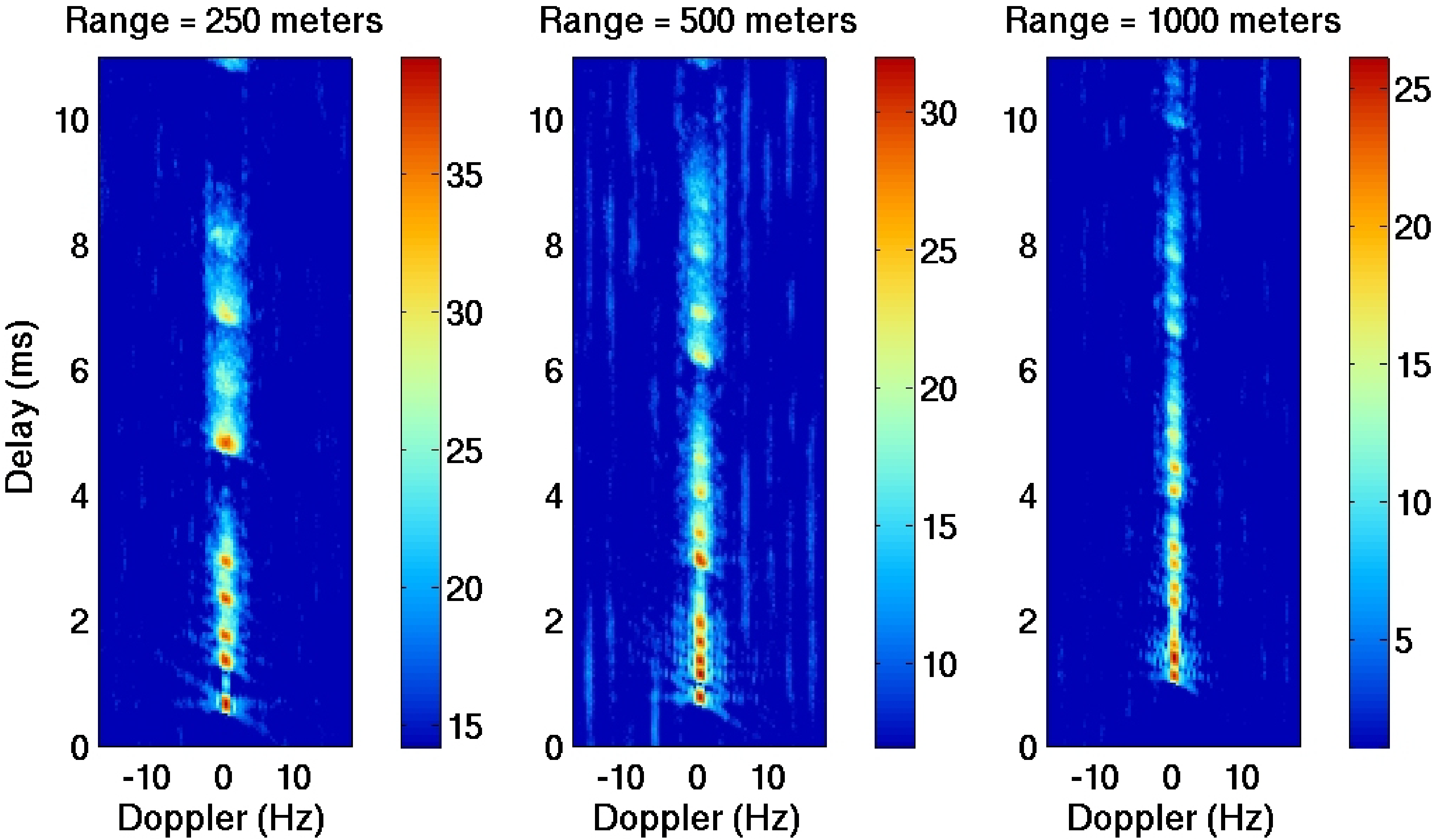
    Long range (1000 km): <1 kHz

Current State of the Art

- Shallow-water medium-range Acomm:
  - 1st Generation (1960's): Non-coherent FSK, < 500 bps, robust
  - 2nd Generation (1990's): coherent PSK + SIMO+DFE, 5 kbps, some times works
  - Recent ONR effort: MIMO, moving Tx/Rx, data rate > 20 kbps, robust
- Major Players in US:
  - WHOI and MIT (Jim Preisig, Lee Freitag, Greg Wornell)
  - Northeast U (Milica Stojanovic) *U Conn (Shengli Zhou)
  - UIUC (Andy Singer) *U Florida (Jian Li) * NRL (T.C. Yang)
  - Missouri S&T (Rosa Zheng & Chengshan Xiao)
  - Arizona State (Tolga Duman)
  - Scripps and UCSD (Bill Hodgkiss, John Proakis)
  - U Washington (Jim Ritcey)

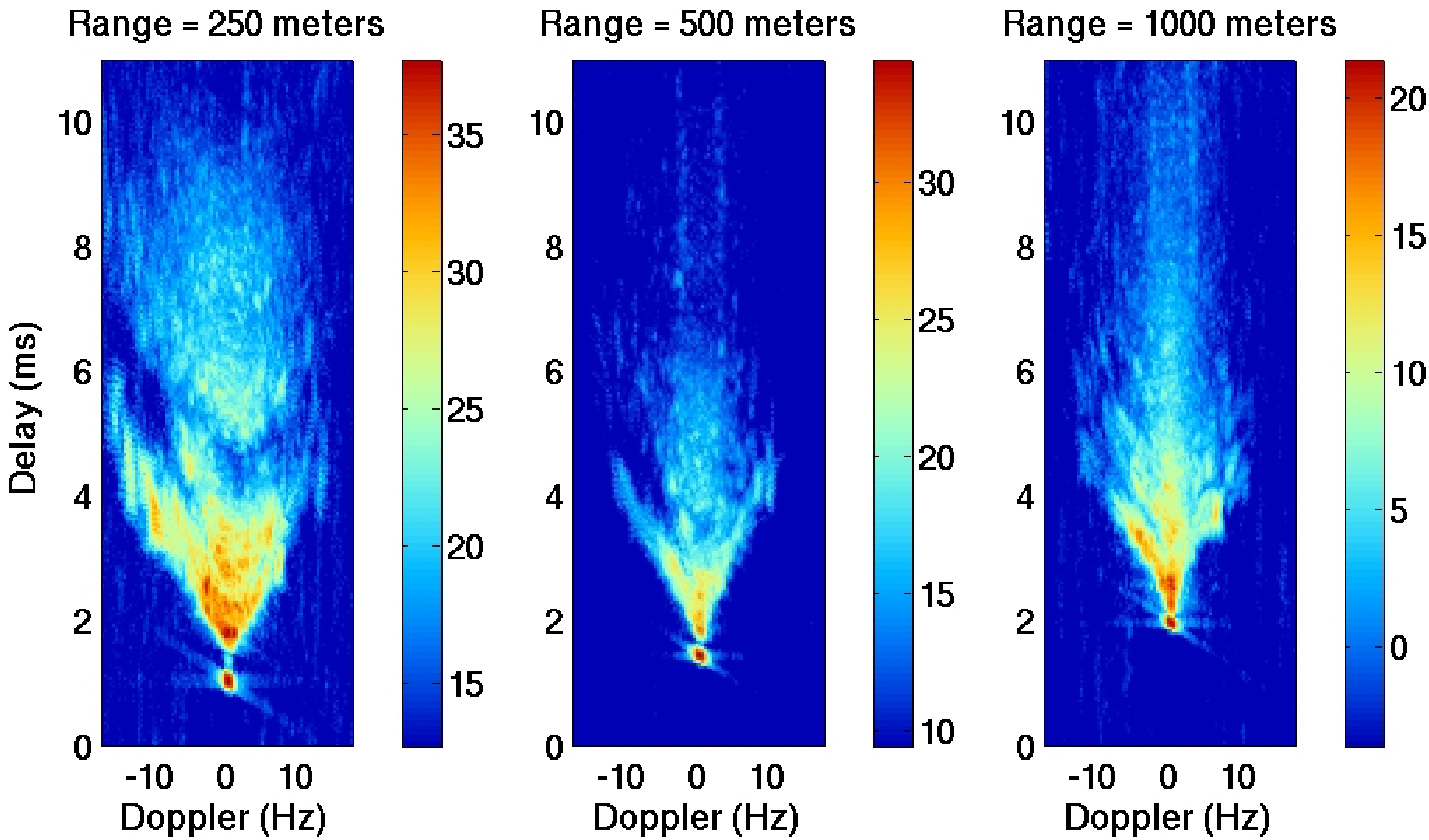
Shallow Water Acoustic Channel

Channel Scattering Functions (0.3 m SWH)



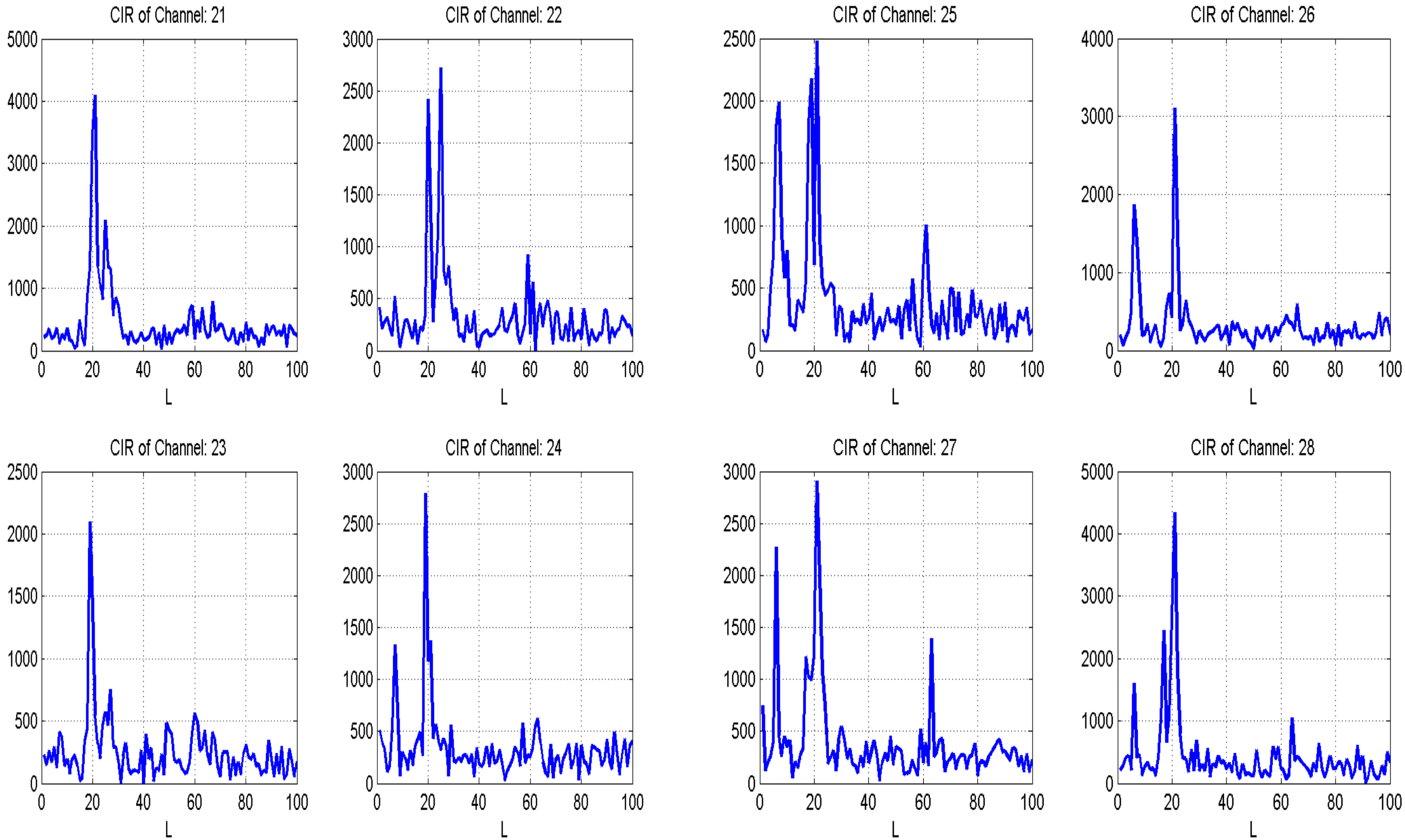
Shallow Water Acoustic Channel 2

Channel Scattering Functions (3.0 m SWH)

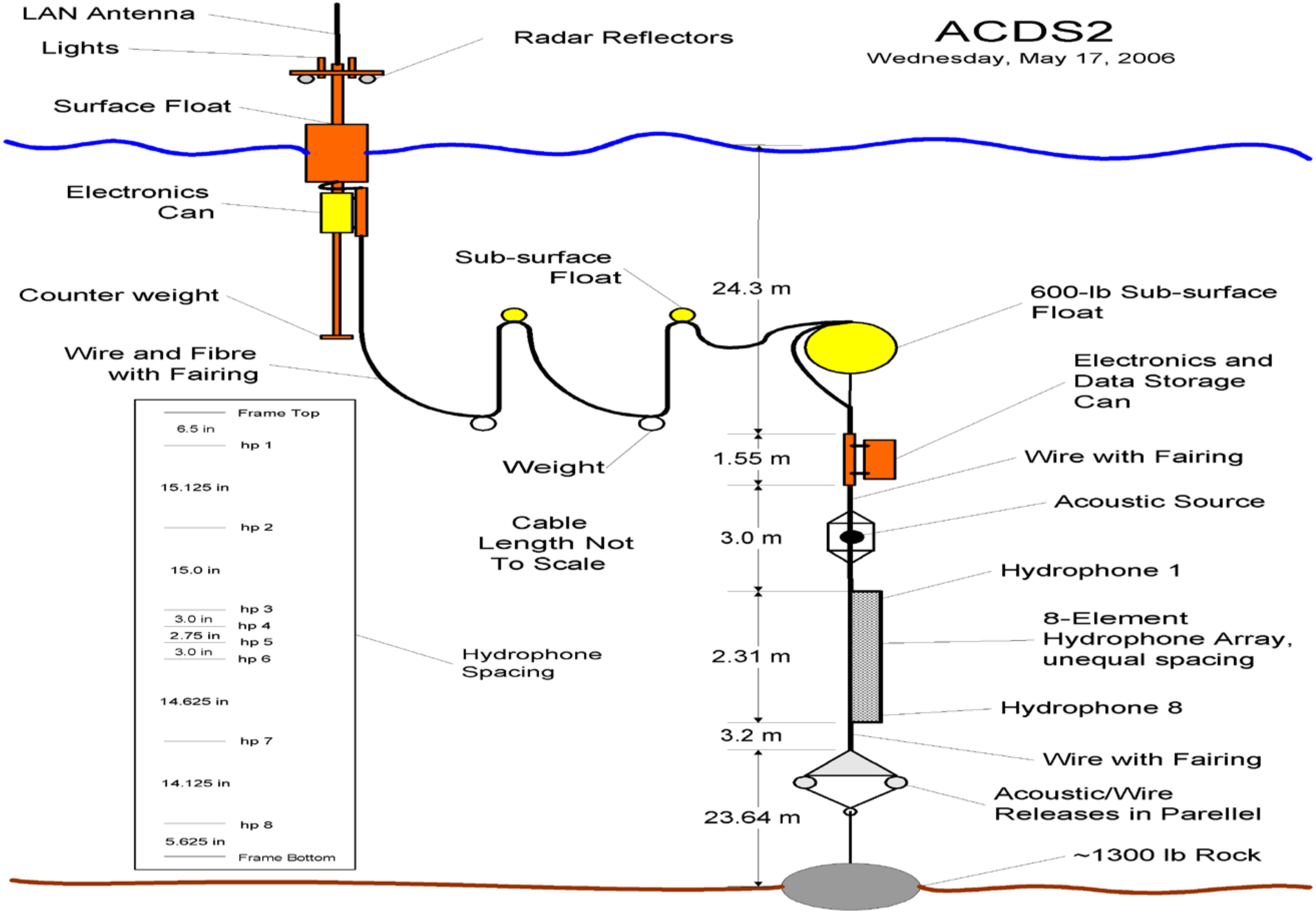


Channel Impulse Responses

UWA MIMO Channels are often asynchronous, non-minimum phase, sparse & inhomogeneous



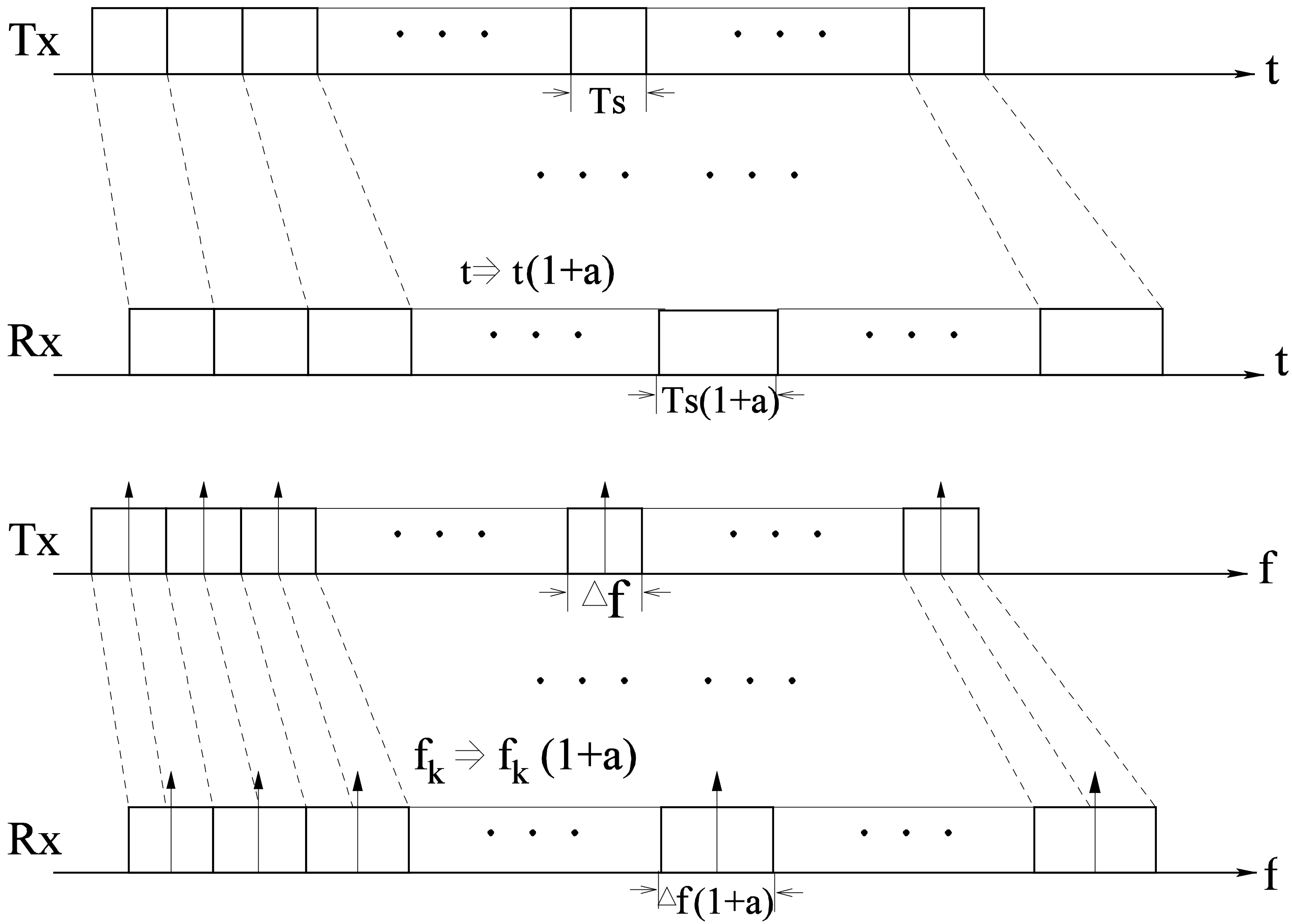
Underwater MIMO



Special Challenge in Acomm

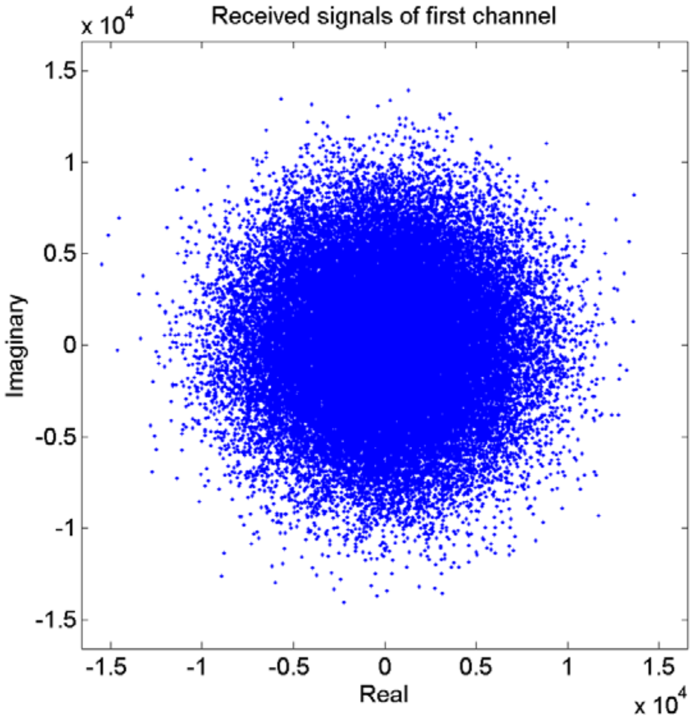
- Triply-Selective fading CIR
  - Spatial selectivity – Angular spread at Tx and Rx
  - Temporal selectivity – Doppler spread
  - Frequency selectivity – Multipath delay spread
- Dilation and Compression
- Shadow Zones – silent (deaf) in some areas
- Very limited BW– a few kHz @ medium range
- Slow propagation – 1500 m/s in ocean

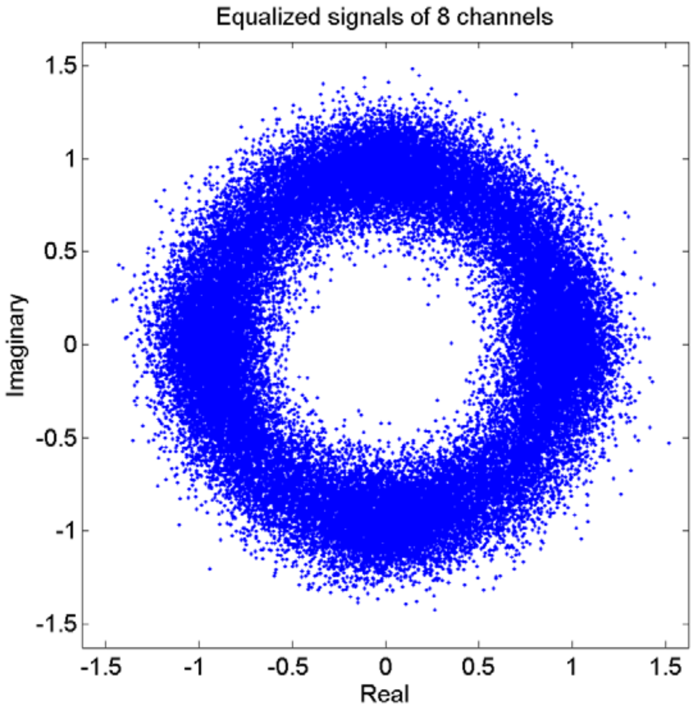
Dilation and Compression



Dilation and Compression

- Conventional Coherent Detection and Equalization
  - phase rotation – effects of Doppler and rescaling error





Current Approaches

***MIMO Single-Carrier Time-domain equalization**

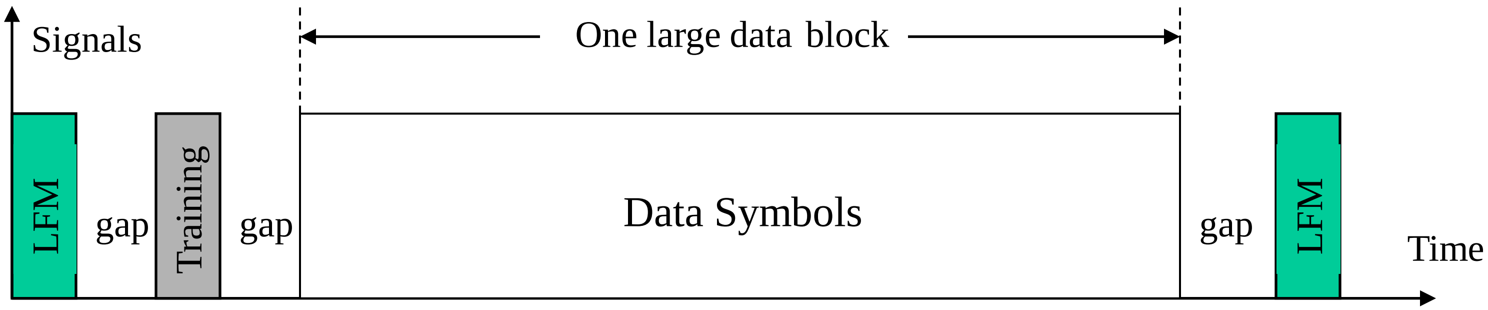
***MIMO Single-Carrier Frequency-domain equalization**

***MIMO Orthogonal Frequency Division Multiplexing (OFDM)**

Typical ACOMM Data Structures

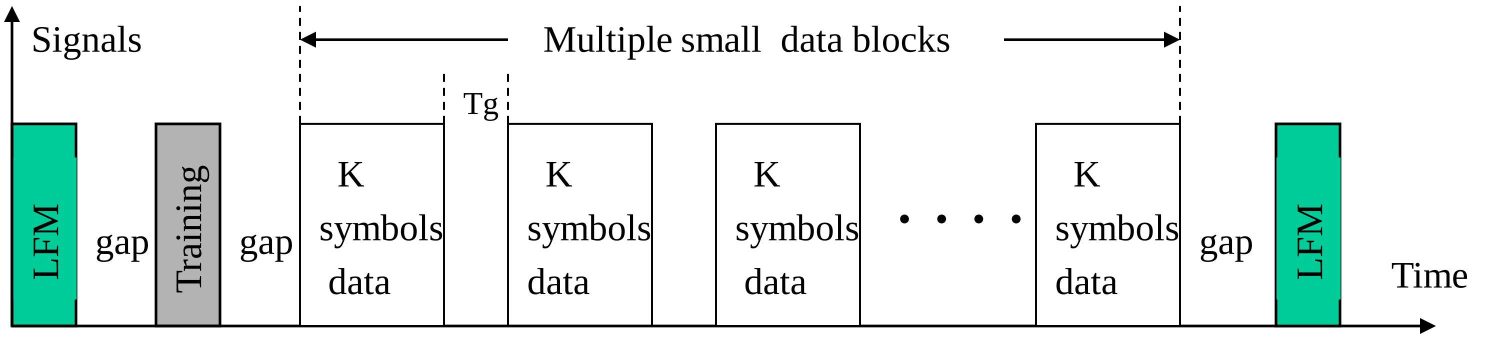
- Time-domain data structure:

Pro: Higher Transmission Data Efficiency
Con: Higher computational complexity



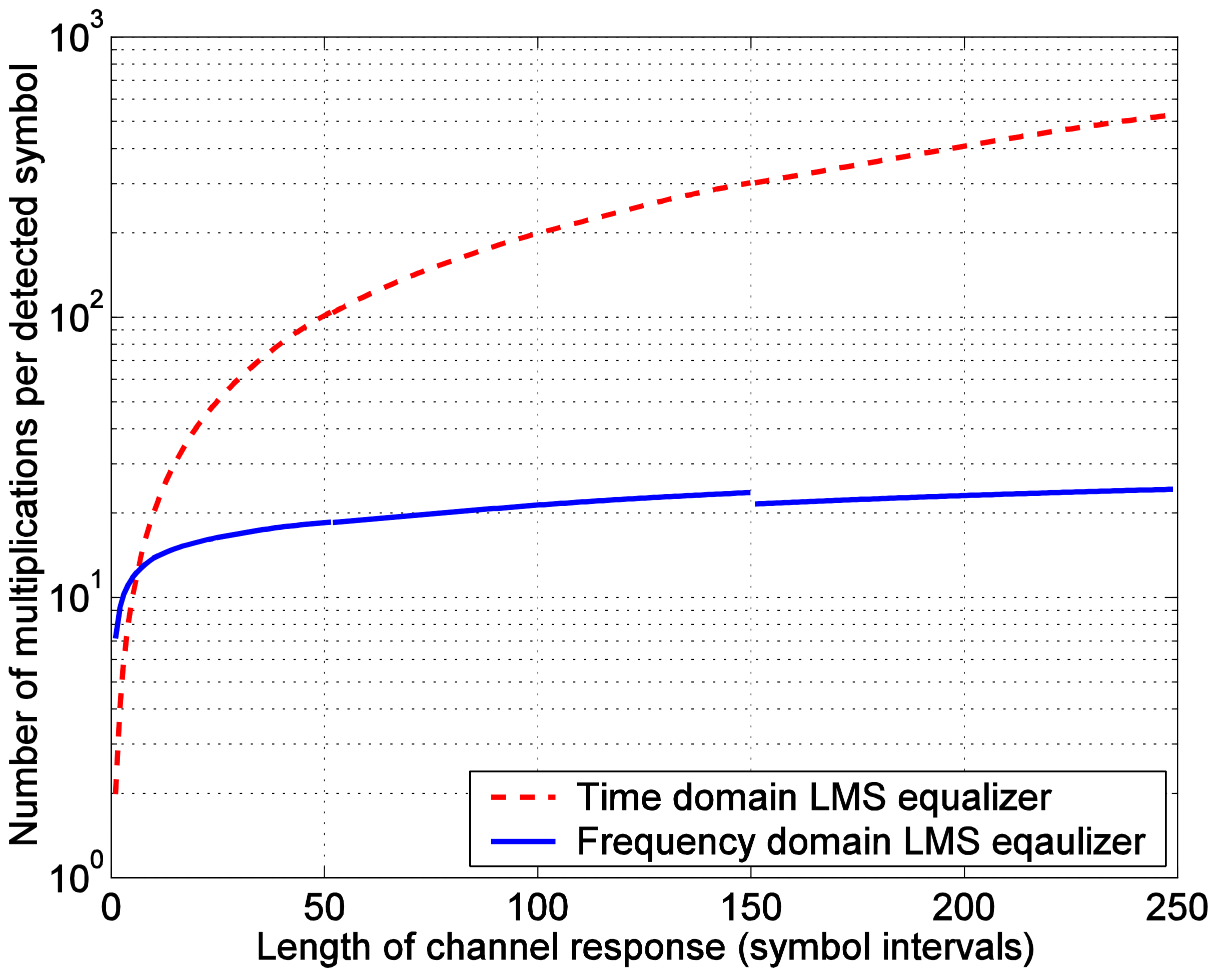
- Frequency-domain data structure:

Pro: Lower computational complexity
Con: Lower Transmission Data Efficiency

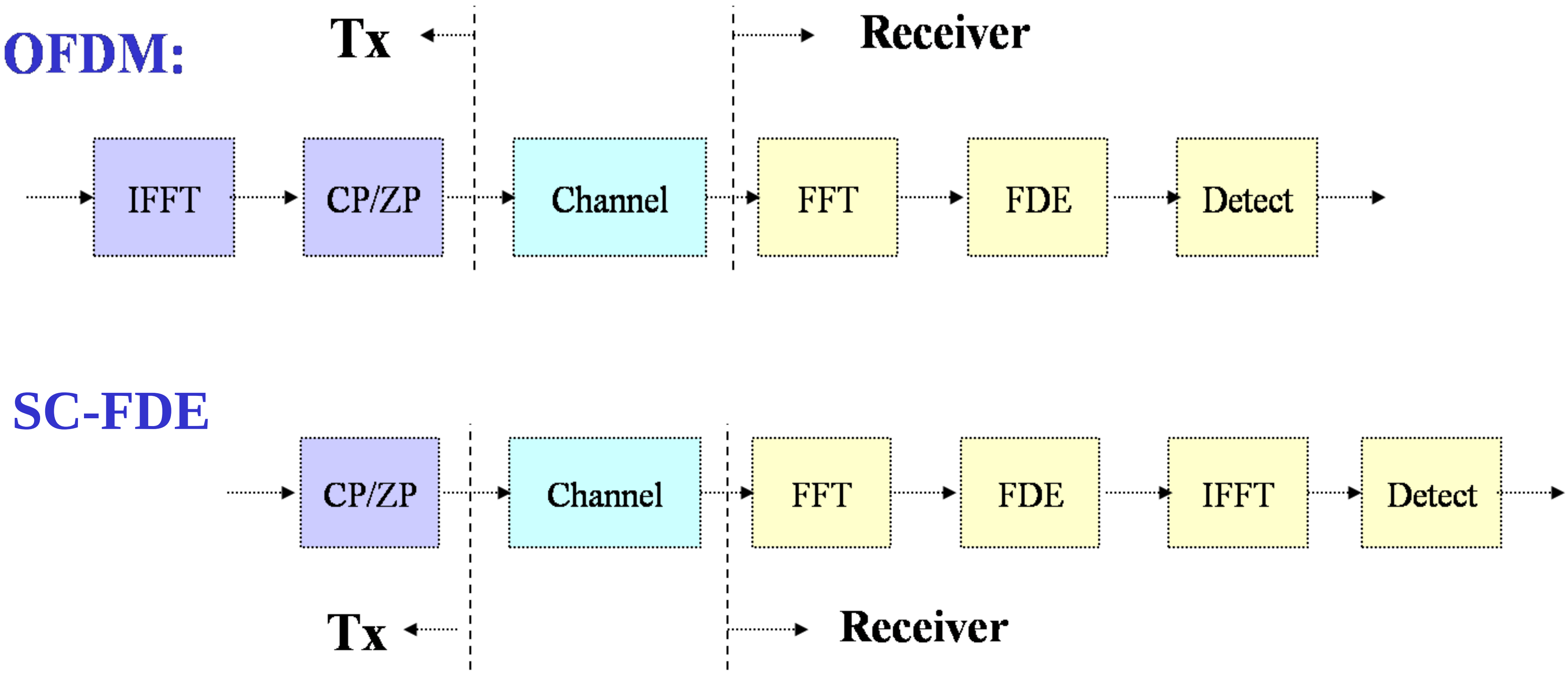


TD vs. FD Approaches

Computational Complexity



OFDM vs. SC-FDE



Summary of Work & Achievements

- Participated in 12 Ocean Experiments and Processed Data from 12 Ocean Experiments
- Published Seven Journal Papers and Thirteen Conference Papers
- Investigated Properties of MIMO Acomm Channels
- Designed & Tested Two Types of Single-Carrier MIMO Transceiver Schemes
  - Single-Carrier *Frequency-Domain* Turbo Equalizer
  - Single-Carrier *Time-Domain* Turbo Equalizer

The12 ACOMM Experiments

	Experiment	Transceiver	Frequency & range
1	**MakaiEx’05**, Kauai, Hawaii SPAWAR, Sept 2005	MIMO, QPSK Turbo code	fc=32 kHz, BW=10 kHz, r = 2 km
2	**UNet’06**, Nova Scotia, Canada NRL, May 2006	SIMO, QPSK Turbo code	fc=17 kHz, BW=4 kHz, r = 1~3 km
3	**AUVFest’07**, Panama City, FL NRL, June 2007	SIMO, QPSK, 8PSK No channel coding	fc=17 kHz, BW=4 kHz, r = 1~3 km
4	**WHOI-VHF’08**, Buzzard’s Bay, MA WHOI, March 2008	MIMO, QPSK, 8PSK No channel coding	Fc=110 kHz, BW=50 kHz, r = < 600m
5	**RACE’08**, Narragansett Bay, RI WHOI, March 2008	MIMO, QPSK, 8PSK No channel coding	fc=11.5 kHz, BW=3.91 kHz, r = <1 km
6	**GLINT08**, Italy WHOI, July 2008	SIMO, QPSK, 8PSK, 16QAM Convolutional coding	Fc=25 kHz, BW=10 kHz r= 1 km
7	**SPACE’08**, Martha’s Vineyard, MA WHOI, Oct. 2008	MIMO, QPSK, 8PSK, 16QAM Convolutional coding	fc=13 kHz, BW=9.77 kHz, r = 60m ~ 1 km
8	**GOMEX’08**, Gulf of Mexico, FL NRL, July 2008	MIMO, QPSK, 8PSK, 16QAM Convolutional coding	fc=17 kHz, BW=4 kHz, r = 1.7 ~ 3 km
9	**WHOI’09**, Buzzard’s Bay, MA WHOI, Dec. 2009	MIMO, QPSK, 8PSK, 16QAM LDPC code	fc= 32.5 kHz, BW=25 kHz, r = 1 ~ 2 km
10	**ACOMM’09**, Off the coast of DE/NJ NRL, May 2009	MIMO, QPSK, 8PSK, 16QAM LDCP code	fc=17 kHz, BW=5 kHz, r= 1 ~ 3 km
11	**MACE10**, Martha’s Vineyard, MA WHOI, July 2010	MIMO, QPSK, 8PSK, 16QAM LDPC code	fc=13 kHz, BW=4.88 kHz, r= 0.5 ~ 4.5 km
12	**ACOMM10**, Off the coast of DE/NJ NRL, July 2010	MIMO, QPSK, 8PSK, 16QAM LDPC code	Fc= 18 kHz, BW=9.375 kHz, r= 1.5 ~ 3 km

Our ACOMM Publications

Published and Accepted Journal Publications

[J1] J. Zhang and Y. R. Zheng, "Frequency-domain Turbo equalization for single-carrier MIMO underwater acoustic communications," *IEEE Trans. Wireless Communications*, vol. 10, no.9, pp. 2872 - 2882. Sep. 2011.

[J2] J. Tao and Y. R. Zheng, "Turbo Equalization for MIMO Underwater Acoustic Communications under Harsh Channel Conditions," *US Navy J. Underwater Acoustics*, accepted in April 2011.

[J3] J. Cross, J. Zhang, and Y. R. Zheng, "Statistics of Underwater Acoustic Channels and Their Effects on Transceiver Performances," *US Navy J. Underwater Acoustics*, accepted. 2011.

[J4] L. Wang, J. Tao, C. Xiao, and T. C. Yang, "Frequency-domain turbo equalization for LDPC-coded single-carrier MIMO underwater acoustic communications," *Wireless Commun. & Mobile Computing*, to appear in late 2011.

[J5] J. Tao, J. Wu, Y. R. Zheng, and C. Xiao, "Enhanced MIMO LMMSE turbo equalization: algorithm, simulations and undersea experimental results," *IEEE Trans. Signal Process.*, Vol. 59, No. 8, pp. 3813-3823. Aug. 2011..

[J5] J. Tao, Y. R. Zheng, C. Xiao, T.C. Yang, "Robust MIMO underwater acoustic communications using turbo block decision-feedback equalization," *IEEE J. Oceanic Engineering*, vol. 35, pp.948-960, Oct. 2010.

[J7] J. Zhang and Y. R. Zheng, "Bandwidth-efficient frequency-domain equalization for single carrier multiple-input multiple-output underwater acoustic communications," *J. Acoust. Soc. Am.* Vol. 128, pp. 2910-2919, Oct, 2010.

[J8] J. Tao, Y. R. Zheng, C. Xiao, T. C. Yang, and W. B. Yang, "Channel equalization for single carrier MIMO underwater acoustic communications," *EURASIP J. Advances in Signal Processing*, special issue on Advanced Equalization Techniques for Wireless Communications, (doi:10.1155/2010/281769), 17 pages, 2010.

[J9] Y. R. Zheng, C. Xiao, T. C. Yang, and W. B. Yang, "Frequency-domain channel estimation and equalization for shallow-water acoustic communications," *Elsevier Journal on Physical Communication*, pp.48-63, March 2010.

Our ACOMM Publications-Cont.

Submitted Journal Publications

[S1]. L. Wang, J. Tao and **Y. R. Zheng,** "Single-Carrier Frequency-Domain Turbo Equalization without Cyclic Prefix or Zero Padding for Underwater Acoustic Communications," *Journal of Acoustic Society of America*, submitted Sep. 2011

[S2] J. Tao and **Y. R. Zheng,** "Turbo Detection for MIMO-OFDM Underwater Acoustic Communications," *Elsevier Journal of Ocean Engineering*, submitted Sep. 2011.

Conference Publications:

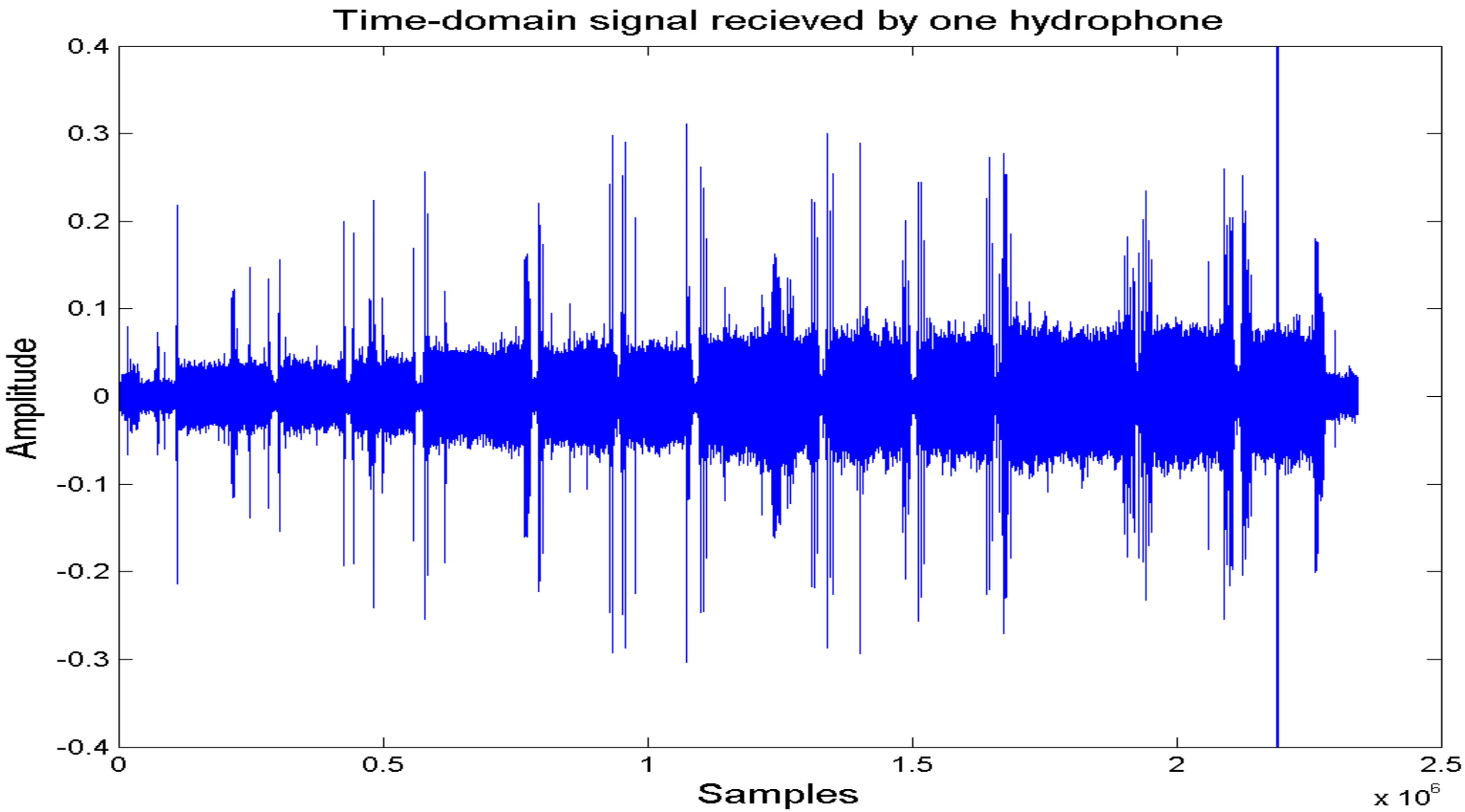
13 conference papers have been presented and published by MTS/IEEE OCEANS Conferences.
3 conference papers presented/published by IEEE MilCom Conference.

SPACE08 Experiment

- Center Carrier frequency is 13 kHz, bandwidth is 9.765625 kHz, Communication ranges are 60m, 200m and 1000m,
  Transducers: 1 ~ 4, and Hydrophones: up to 12
- Modulations: QPSK, 8PSK and 16QAM
- Channel coding: Rate-½ convolutional code [17, 13]
- FFT block length K=1024, 2048 and 4096
- Root raised cosine filter, roll-off factor is 0.2.

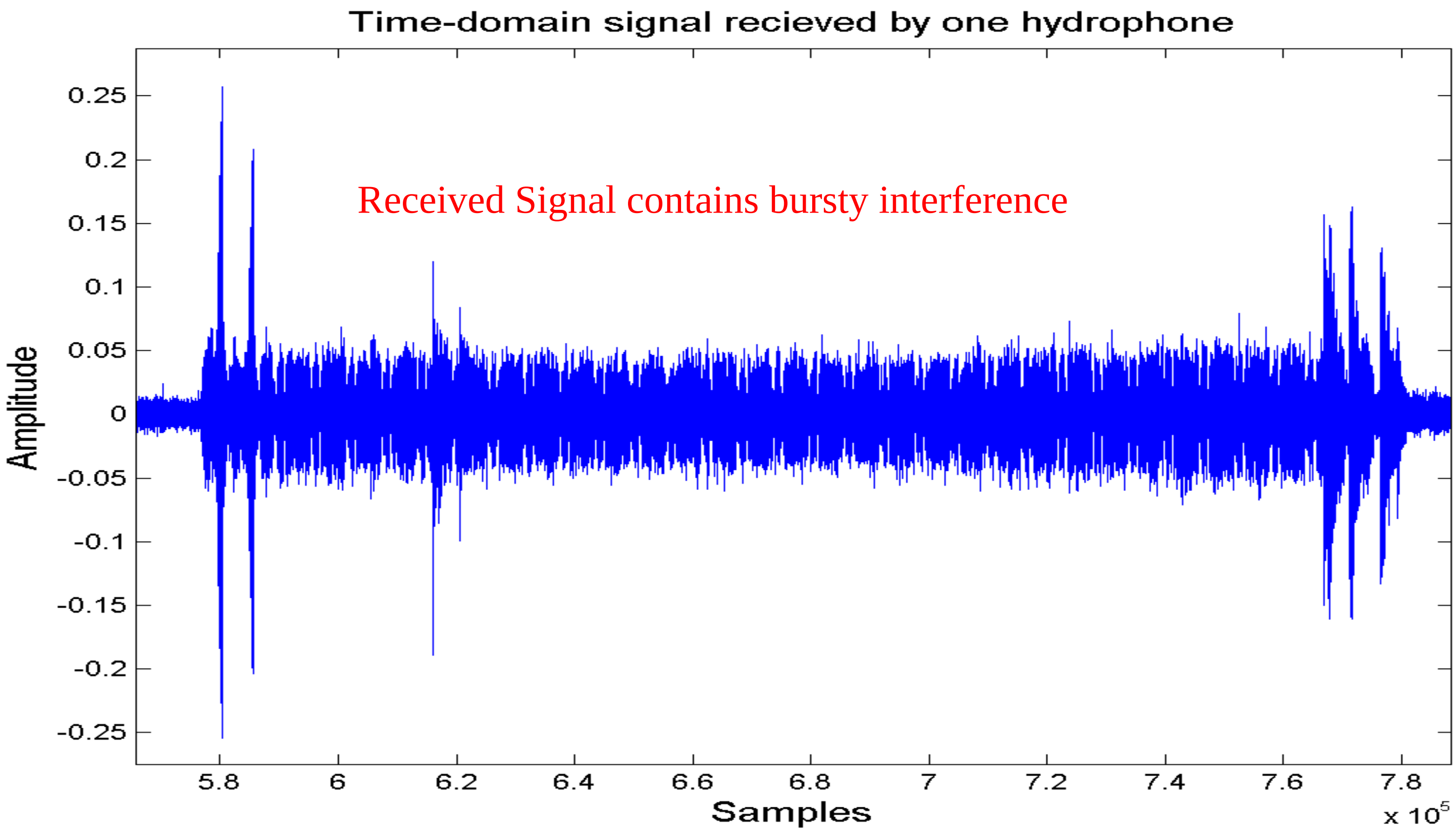
A Sample Received Signal at 1000m

	Gap	1 Tx	2 Tx	3 Tx	4 Tx	Gap	Total
Symbols	20000	117000	130000	143000	155000	20000+937.5	2343750/4
Time	2.048s					2.048+0.096	60s

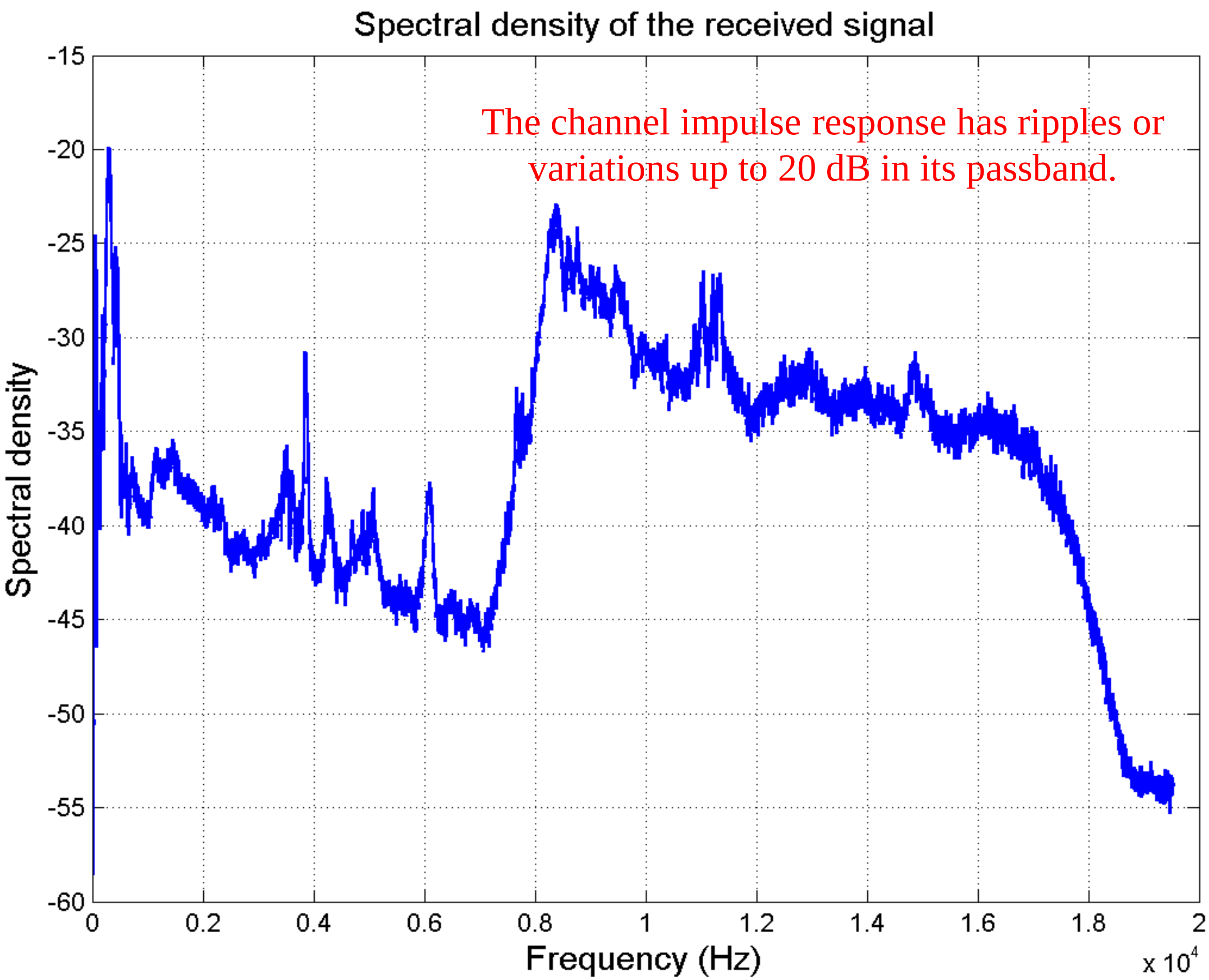


2-Tx, A Received Signal at 1000m

2 Tx	K=1024	K=2048	K=4096	Sub-Total
Symbols	54000	39000	37000	130000
Time				13.3120

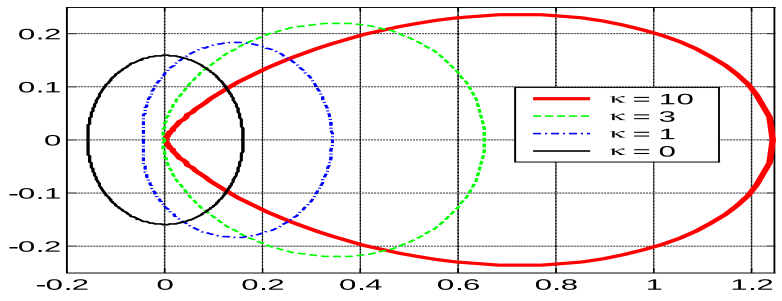


PSD of the Received Signal at 1000m

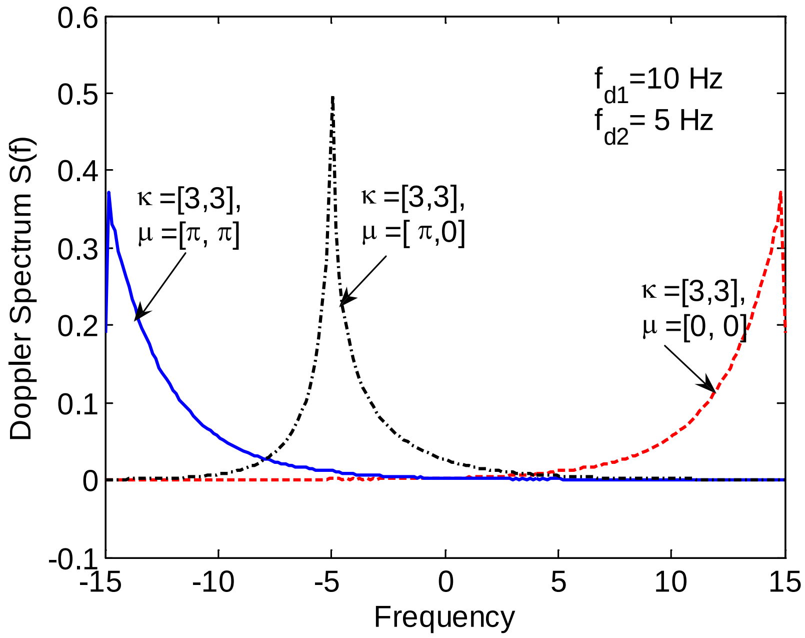


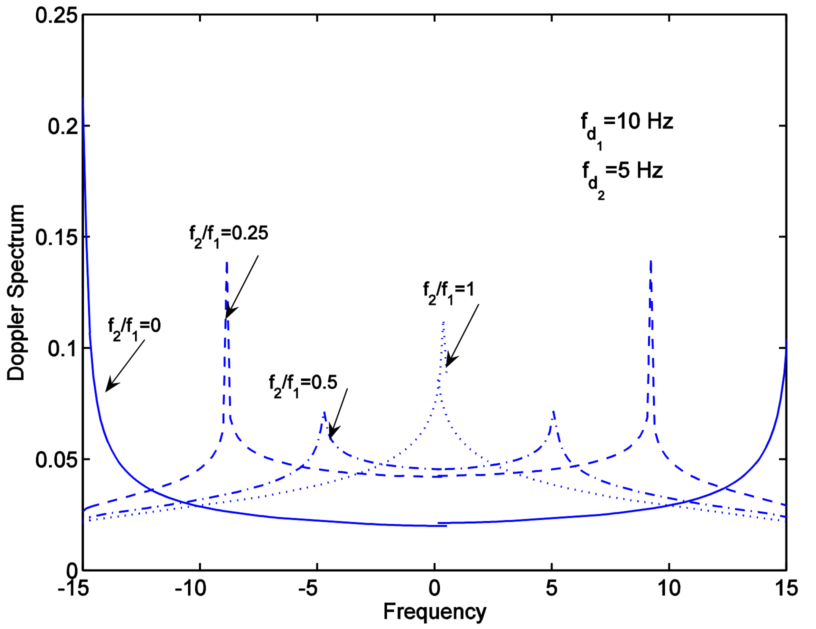
ACOMM Channel Statistical Properties

- Compound K pdf instead of Rayleigh fading
- Non-isotropic Scattering instead of Isotropic Scattering: AoD & AoA are von Mises distributed



- Doppler Spectrum is different!





Effect of Spatial Correlation- SPACE'08 Experiment Results

Spatial Correlation

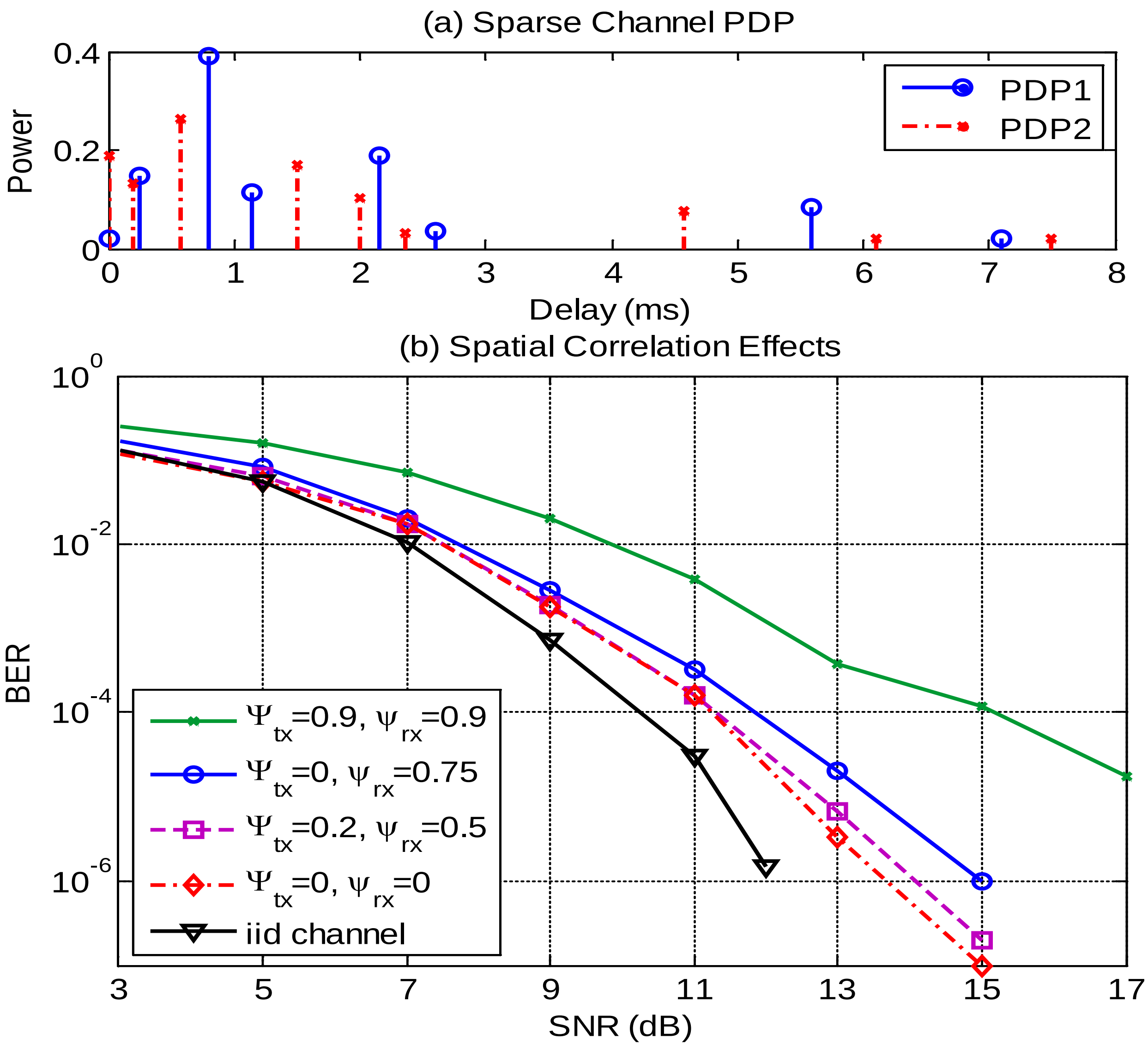
Hydrophone #	Ψtx	Ψrx
Rx 1 - Rx2	[1.00 0.88-j0.11; 0.88- j0.11 0.80]	[0.76 0.77 + j0.41; 0.77+ j0.41 1.00]
Rx 1 - Rx4	[1.00 0.71-j0.27; 0.71-j0.27 0.87]	[0.61 0.72 + j0.31; 0.72+ j0.31 1.00]
Rx1 - Rx10	[1.00 0.71-j0.60; 0.71- j0.60 0.86]	[0.40 0.60 + j0.21; 0.60+ j0.21 1.00]

FD Turbo Equalizer Performance

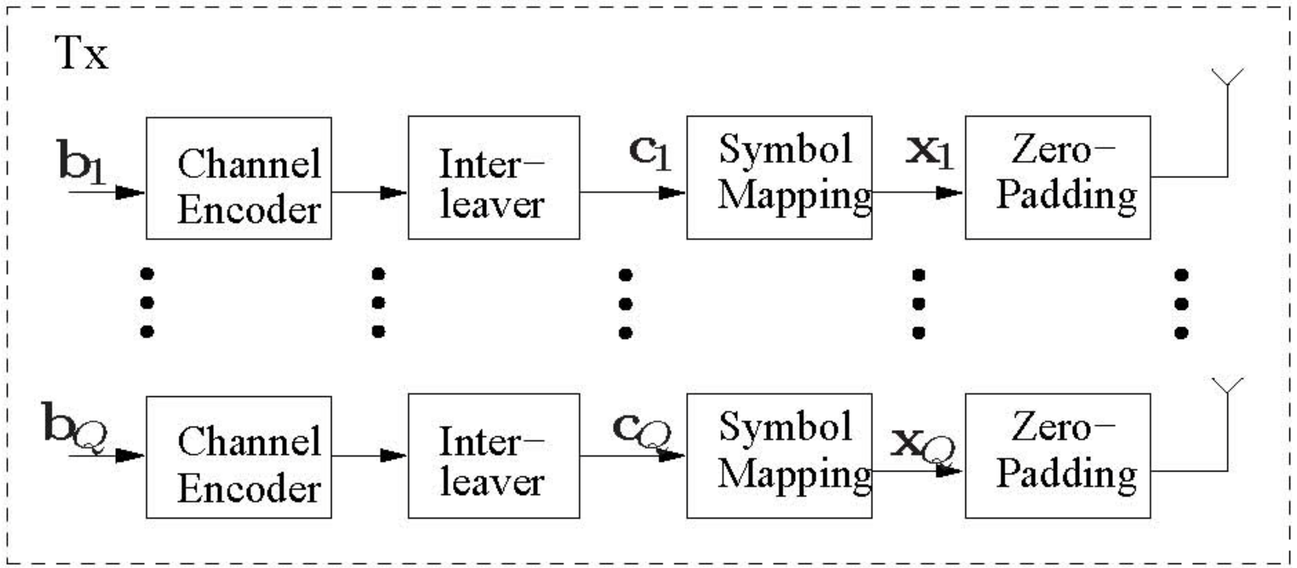
Range	Rx 1,2,3,4	Rx 1,4,7,10	Rx 1--10
200 m	1.58e-1	3.03e-2	9.97e-3
1000 m	2.23e-1	9.3e-2	9.29e-2

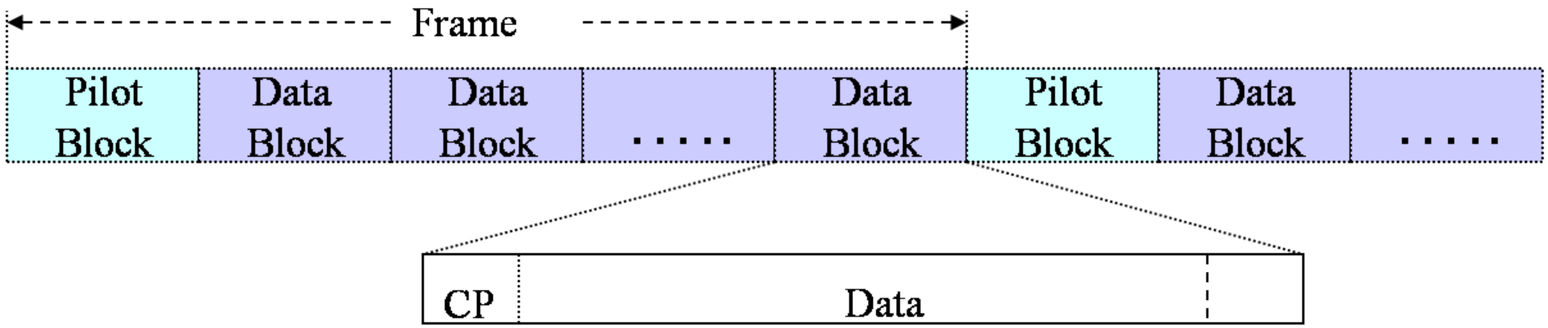
Aperture gains > number of hydrophones!

Effect of Spatial Correlation-
2x4 MIMO Simulation



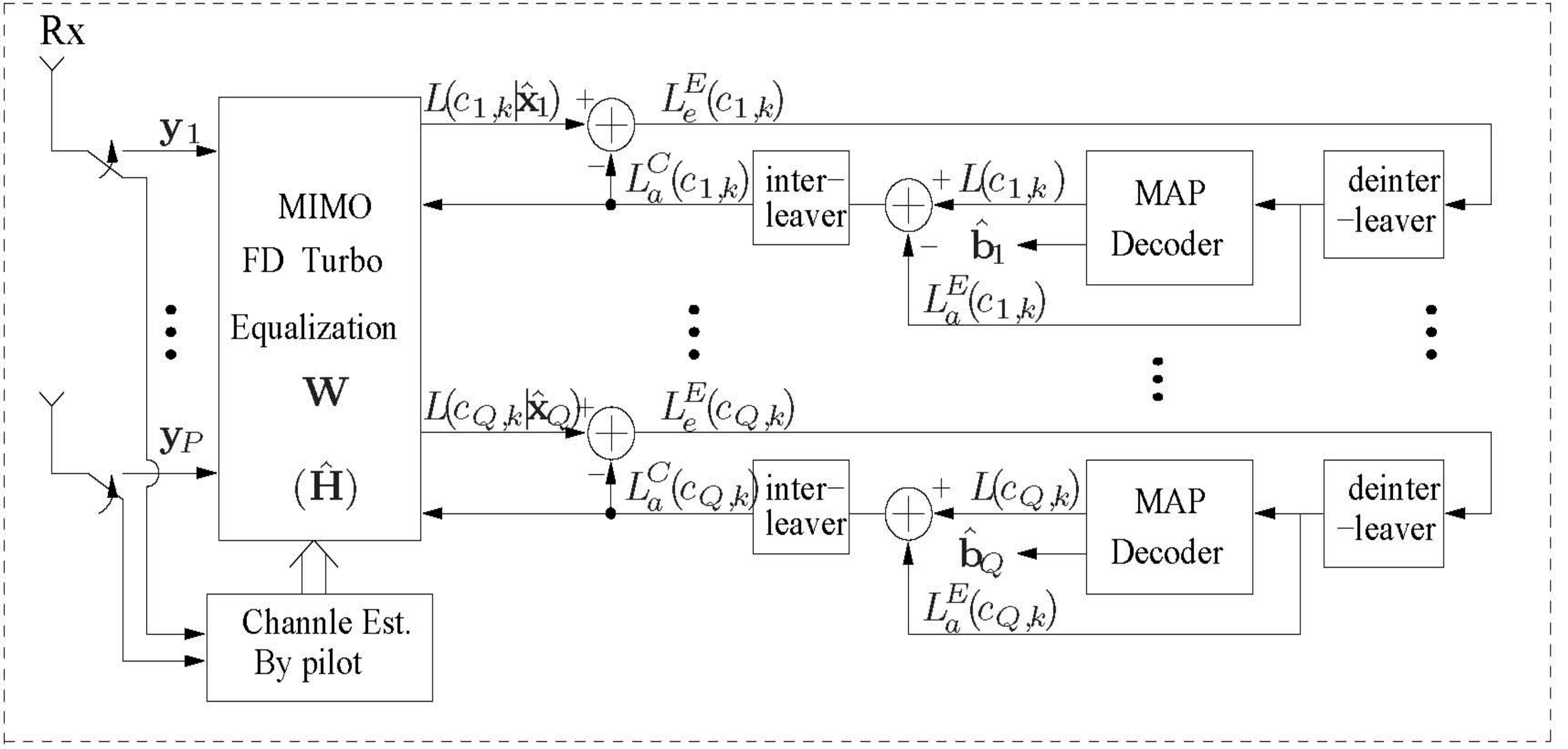
MIMO Single Carrier Transceiver





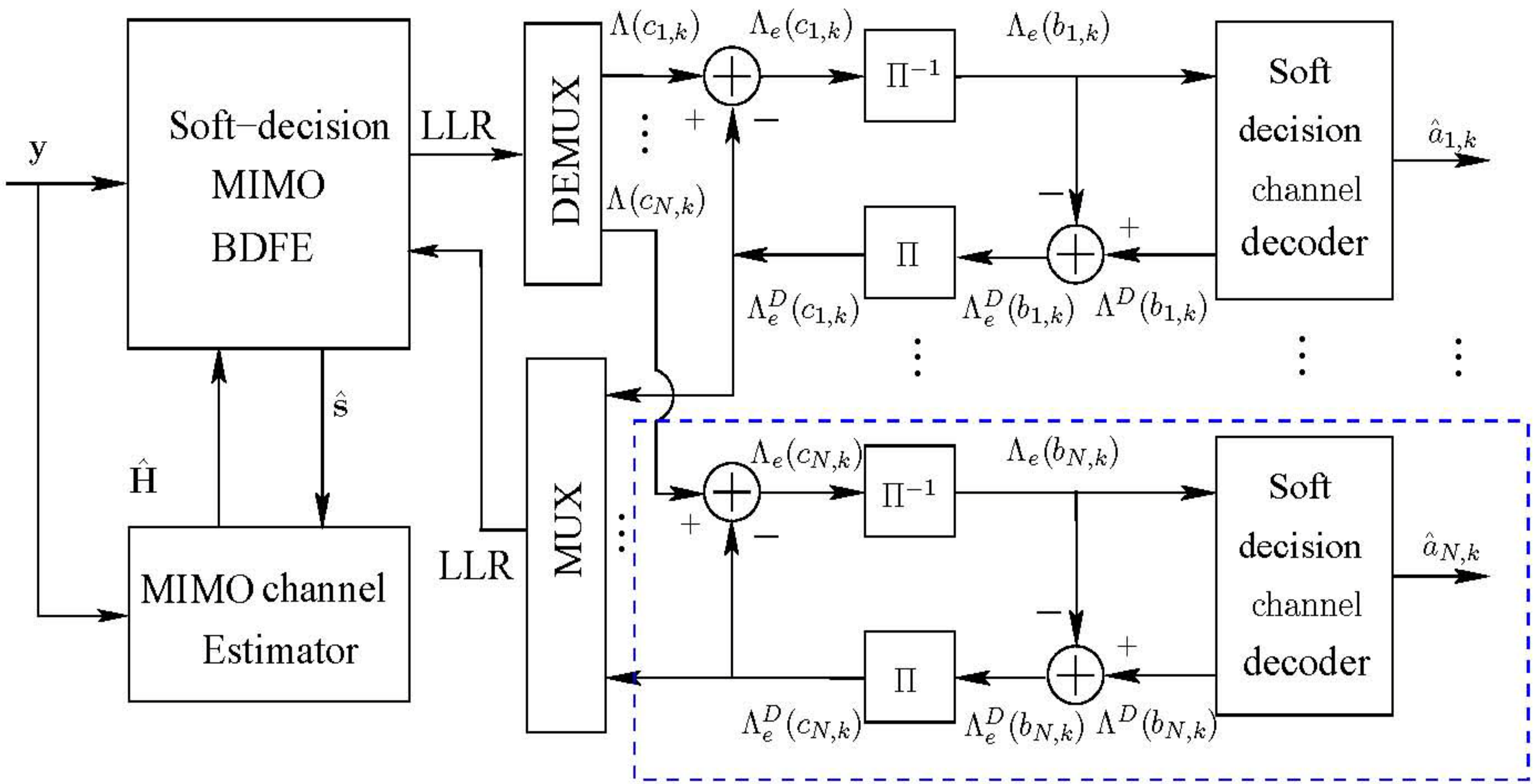
FD MIMO Turbo Equalizer

FD Receiver Structure

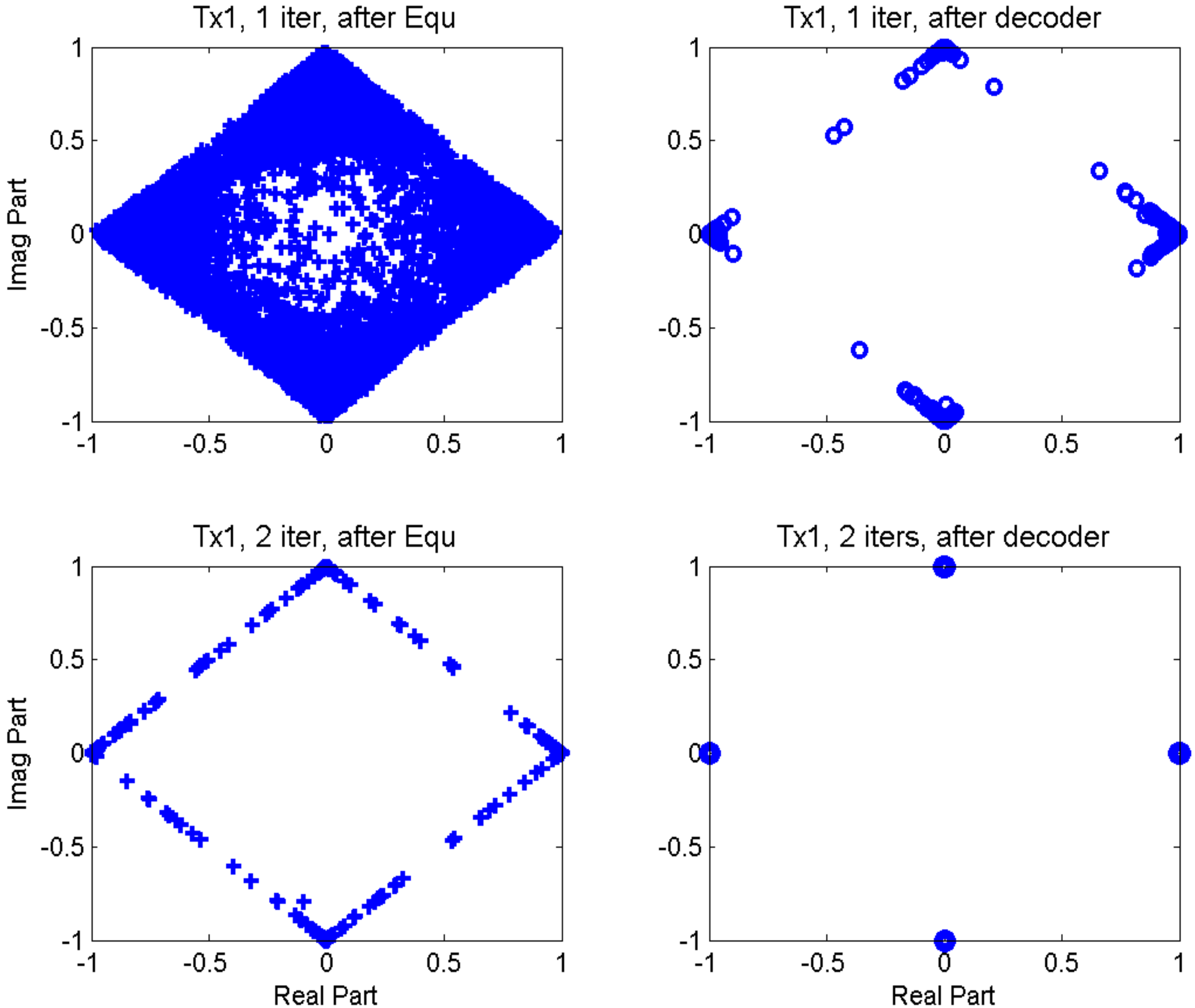


TD Receiver Architecture

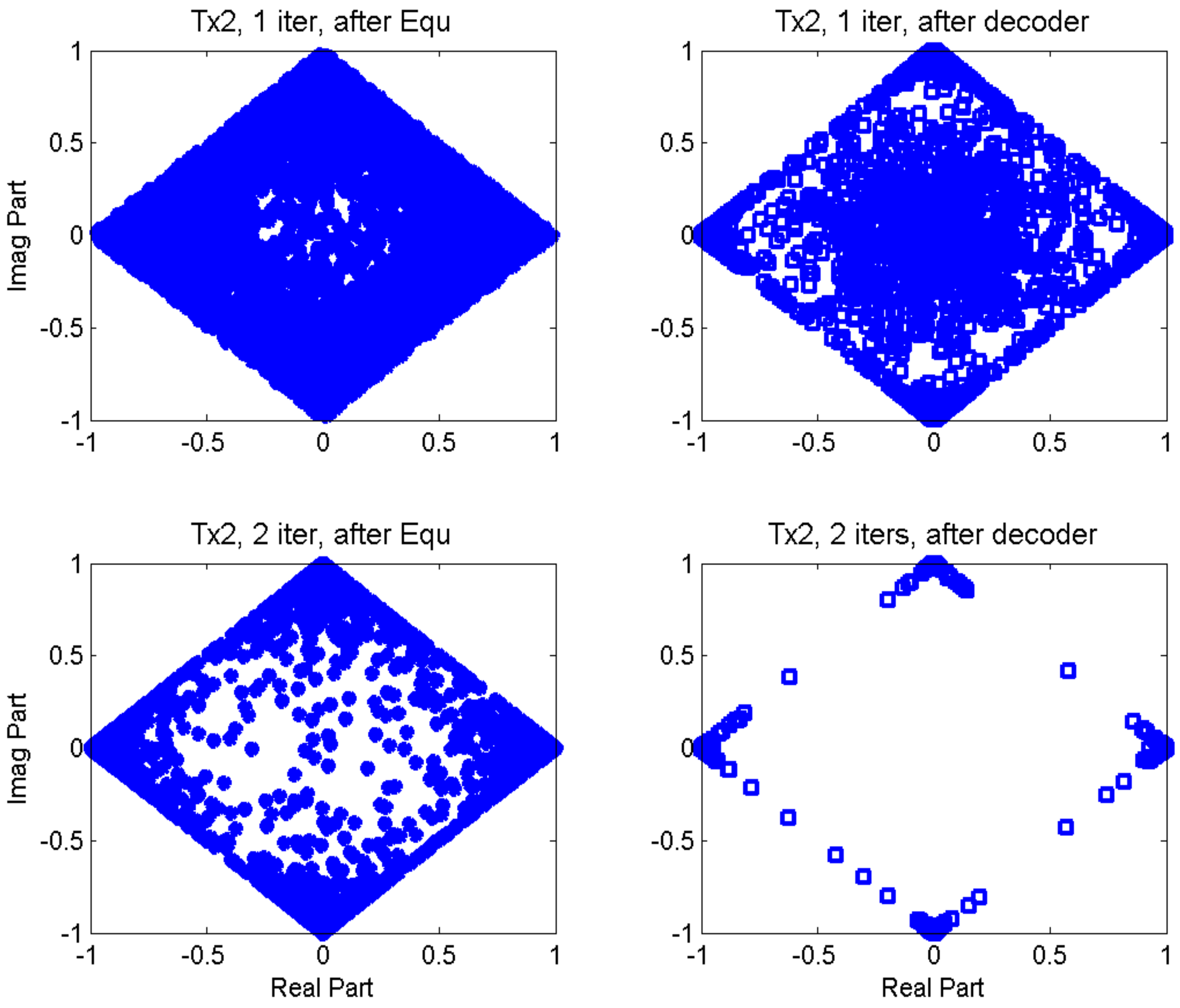
- Receiver: *M* hydrophone time-domain joint MIMO BDFE,
- *N* parallel channel decoders, iterative data



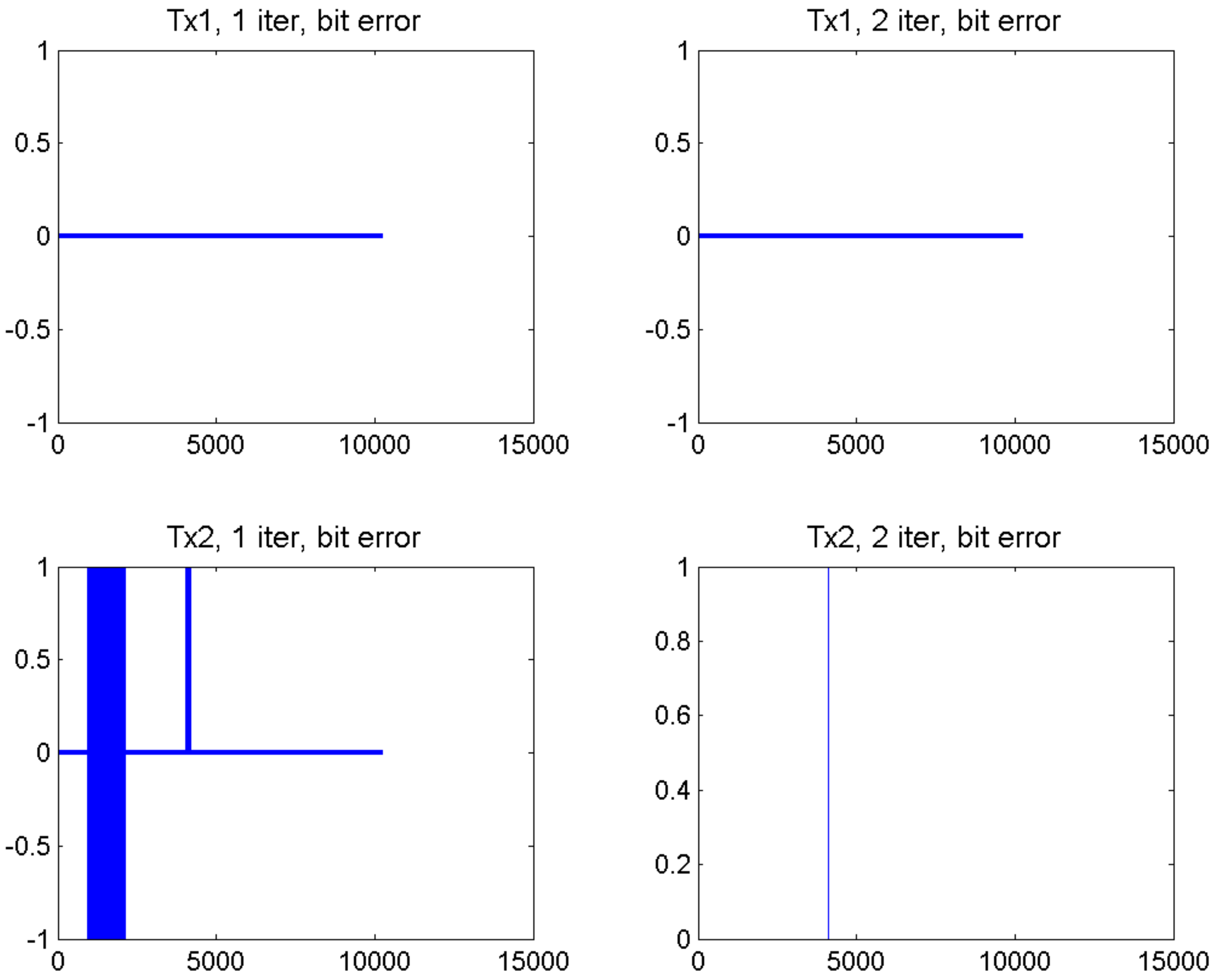
2-Tx, QPSK, Turbo Equalizer Outputs 1000m



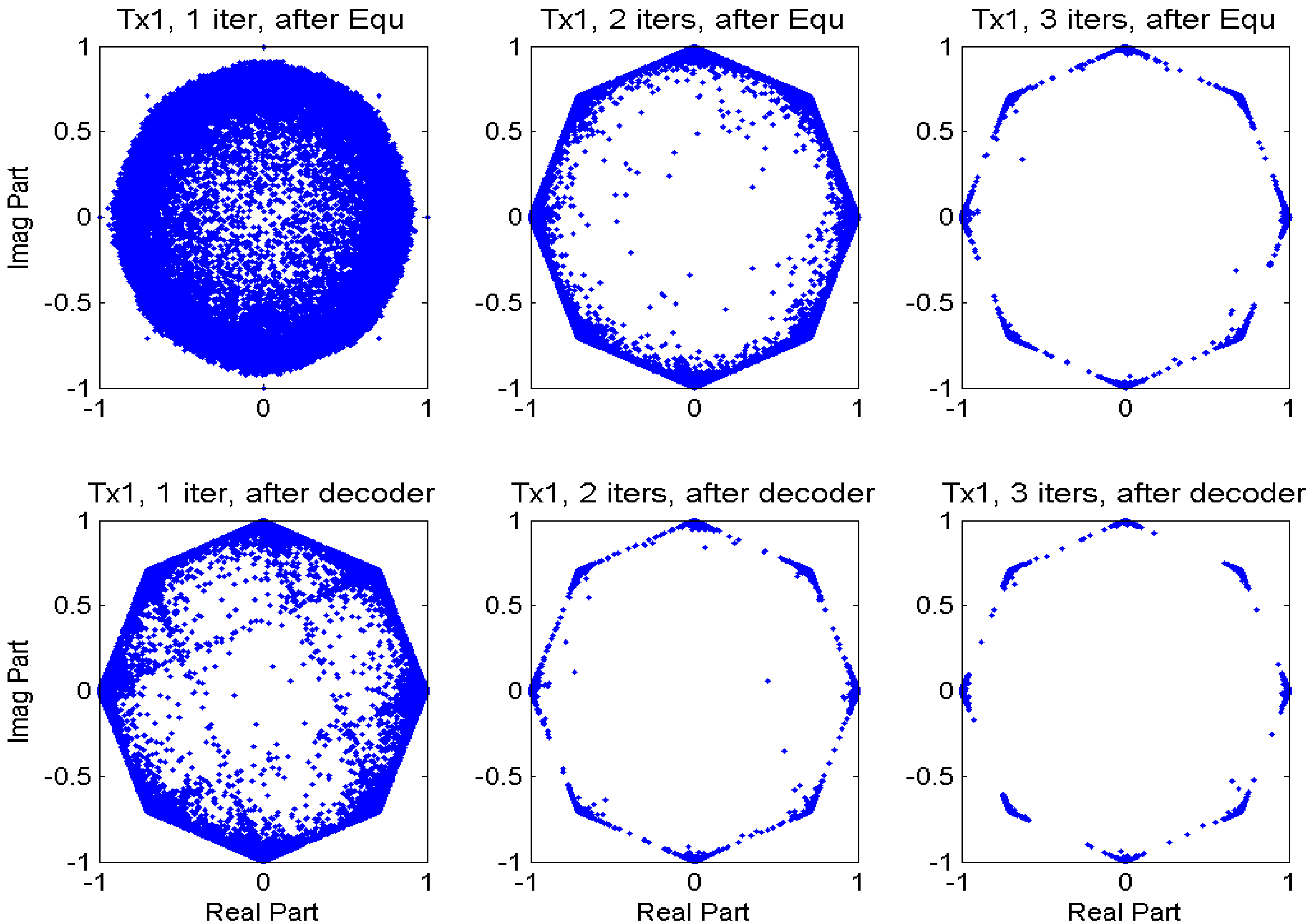
2-Tx, QPSK, Turbo Equalizer Outputs at 1000m



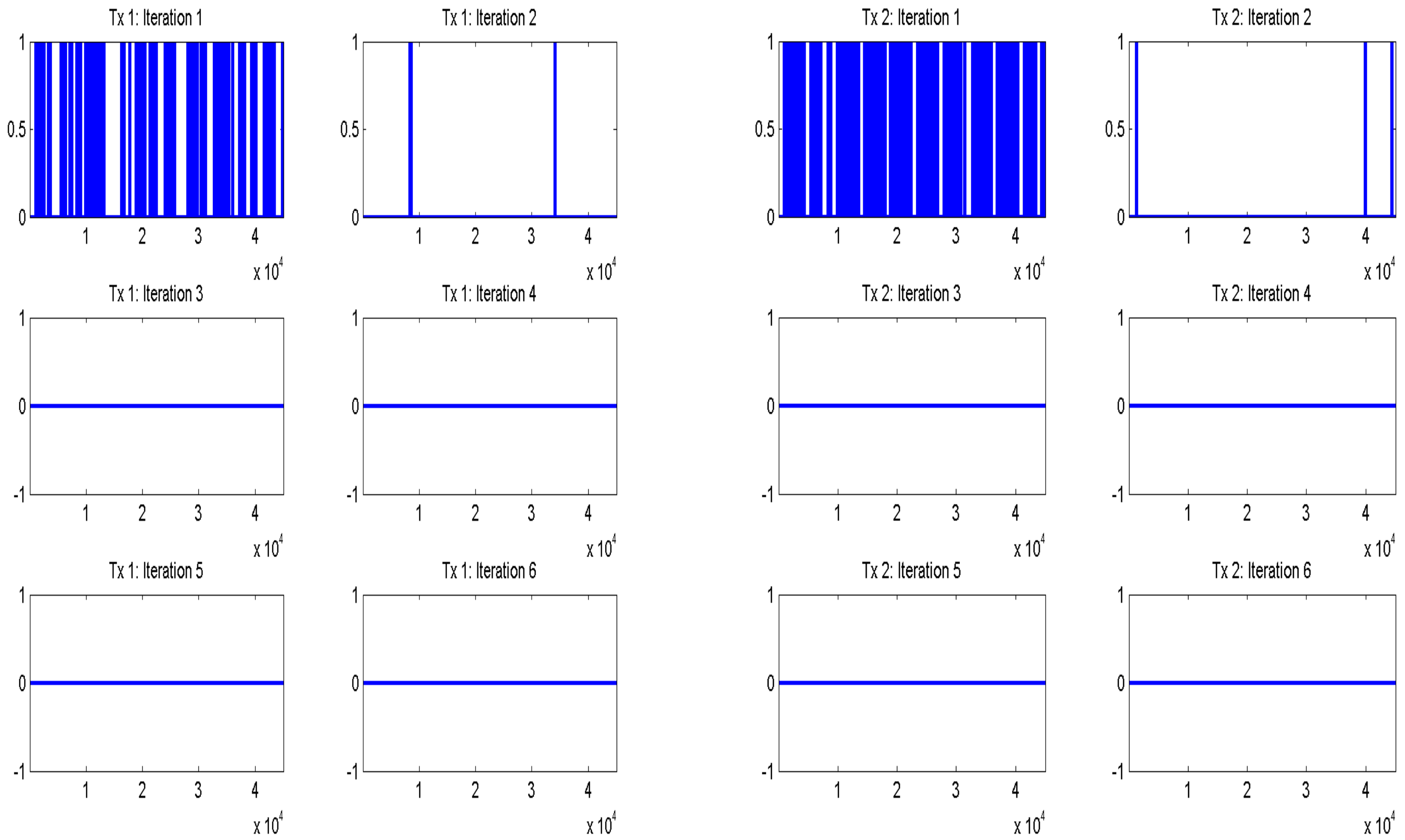
2-Tx, QPSK, Bit Error Locations (1000m)



2-Tx, 8PSK, Turbo Equalizer Outputs, 1000m



2-Tx, 8PSK, Bit Error Locations (1000m)



Conclusion and Future Work

Conclusions:

- MIMO Turbo Equalization works: 2-by-12 to 4-by-12
- Data efficiency: 75-80% (compare with OFDM: 50%)
- Data rate @ 10 kHz BW: 20--60 kbps
- Robustness: greatly improved

Future Work:

- Hardware Implementation
- moving MIMO
- Channel Statistic Information at Tx
- Multiple Access Technologies

Missouri University of Science and Technology, Rolla, Missouri USA

Building a Better Missouri S&T

- **Havener Student Center**
  - **Opened January 2005**

- **Toomey Hall – Mechanical & Aerospace Engineering**
  - **Phase I Complete** **Phase II Complete Fall 2009**

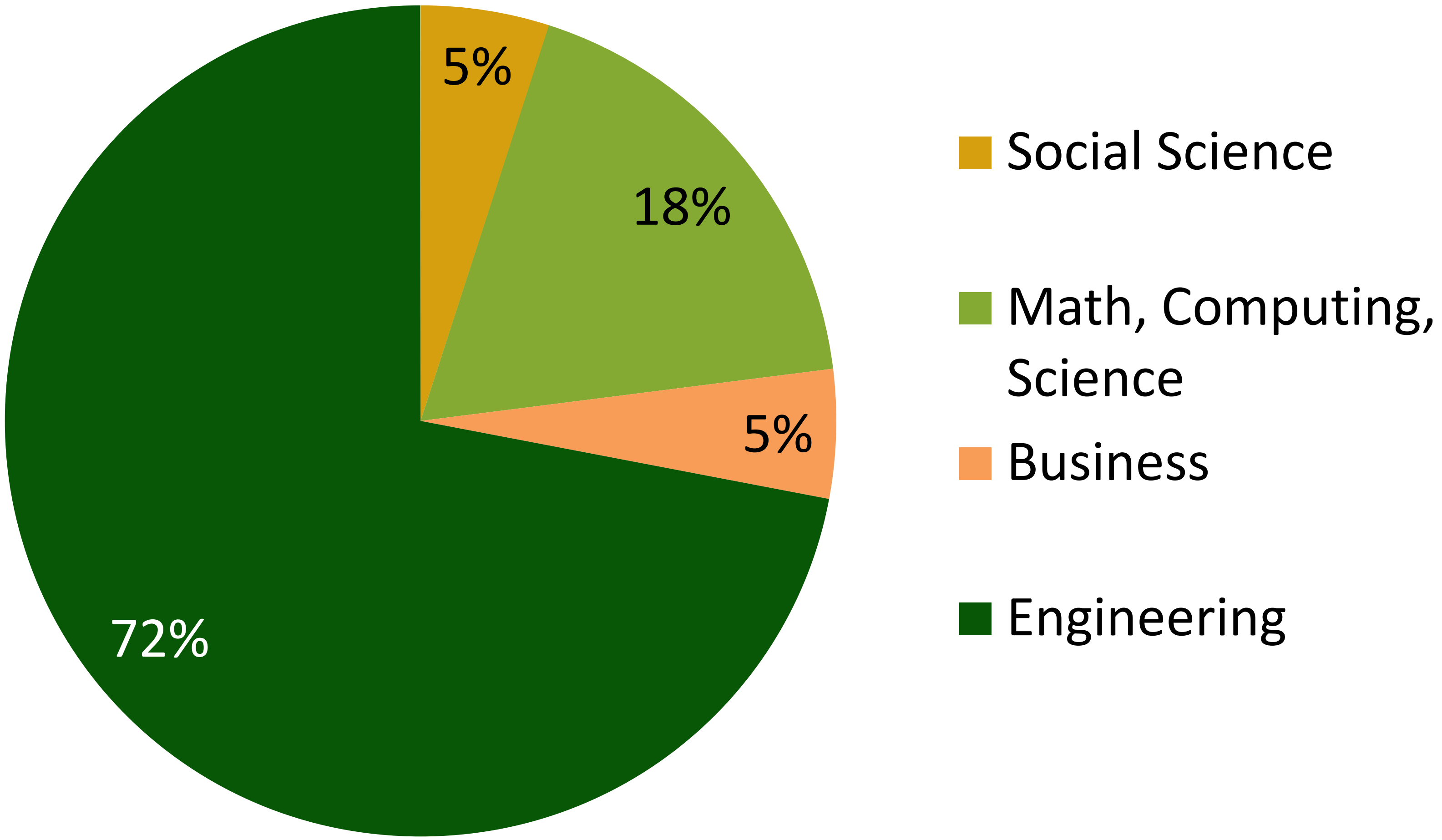
Grad Fast Facts

- Over 35 Graduate Certificates offered
- 28 Master's Programs offered
- 20 PhD programs offered
- 11 degrees offered entirely on-line
- 175 classes offered on-line
- 54% international grad students (on-campus)
- 1700 students from over 50 countries
- Graduate Studies website and admissions website:

http://grad.mst.edu/index.html

http://grad.mst.edu/prospectivestudents/admissionsreqs.html

Graduate Enrollment total ~1700



- **Grad Enrollment: from India: ~ 300, from China: ~400**