Underwater Wireless Communications: Overview and Recent Progress

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Why Underwater Wireless?

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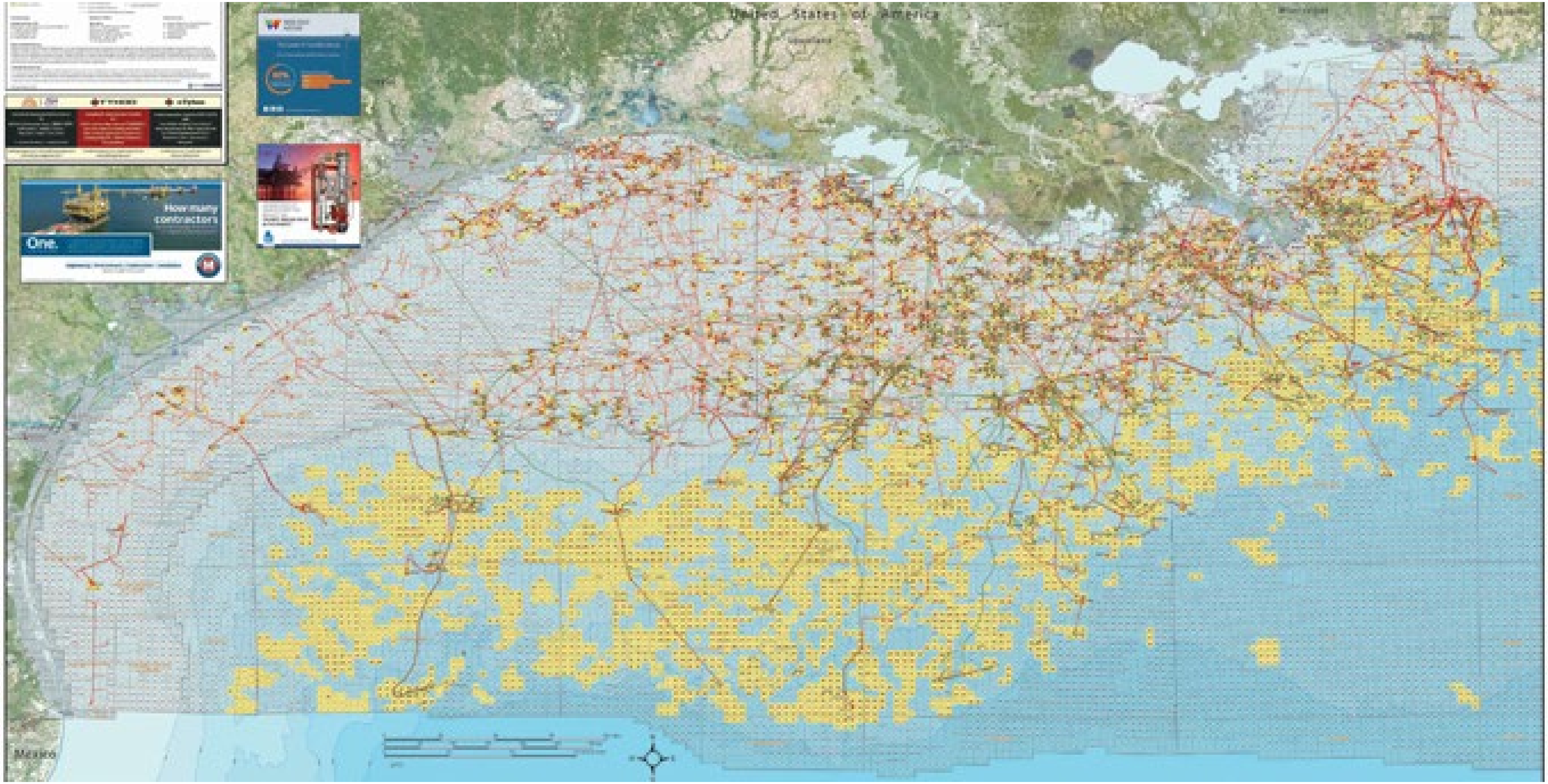
- Water covers >70% of Earth Surface, and 50% of USA territory lies under the sea.
- Ocean provides:
  - Food, Fuel, Fun;
- Life began in the ocean over 3.5 billion years ago, but over 95% of the ocean is unseen by human eyes

Gulf of Mexico Oil and Gas Sites



Underwater Wireless - Bottleneck

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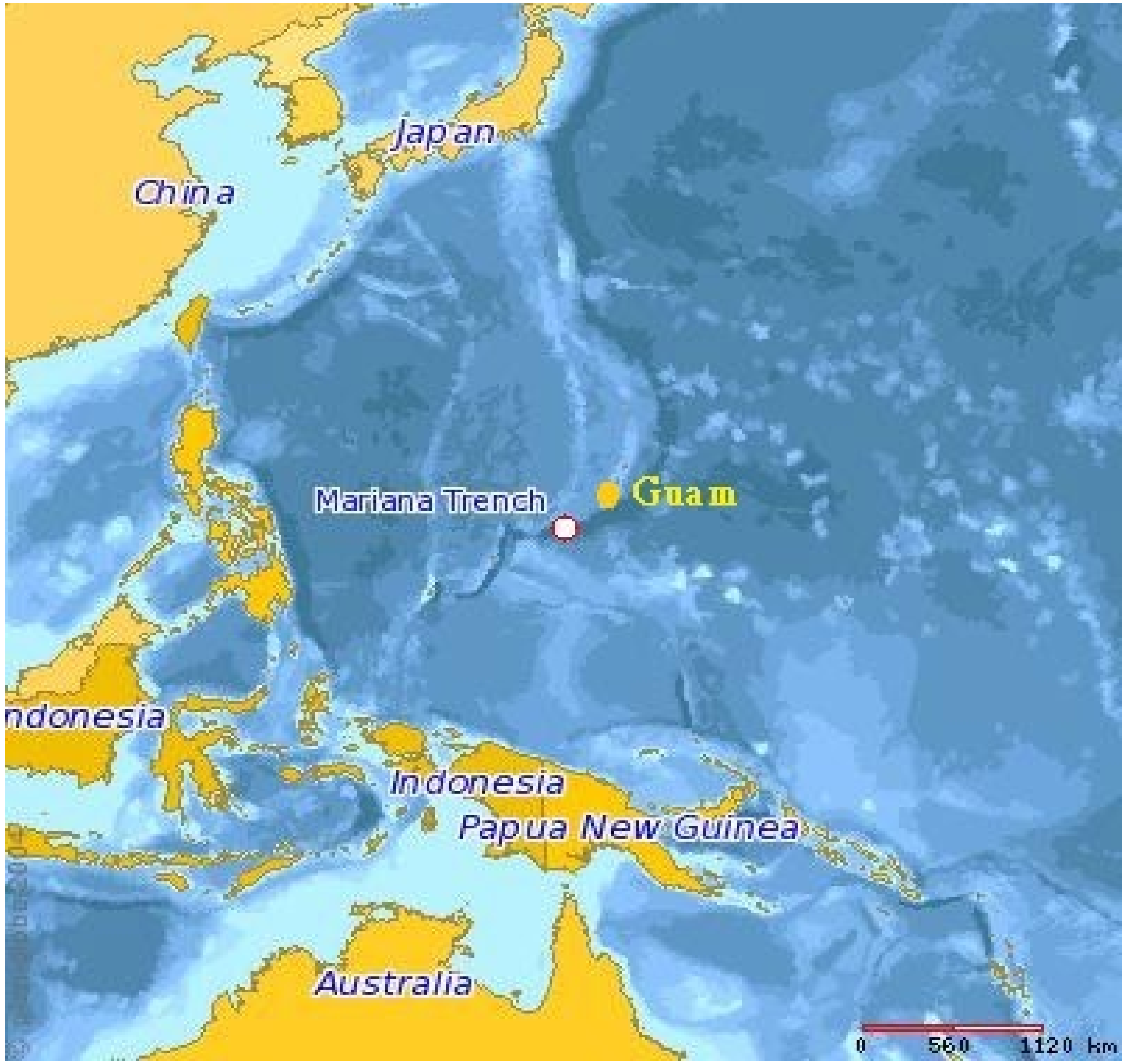
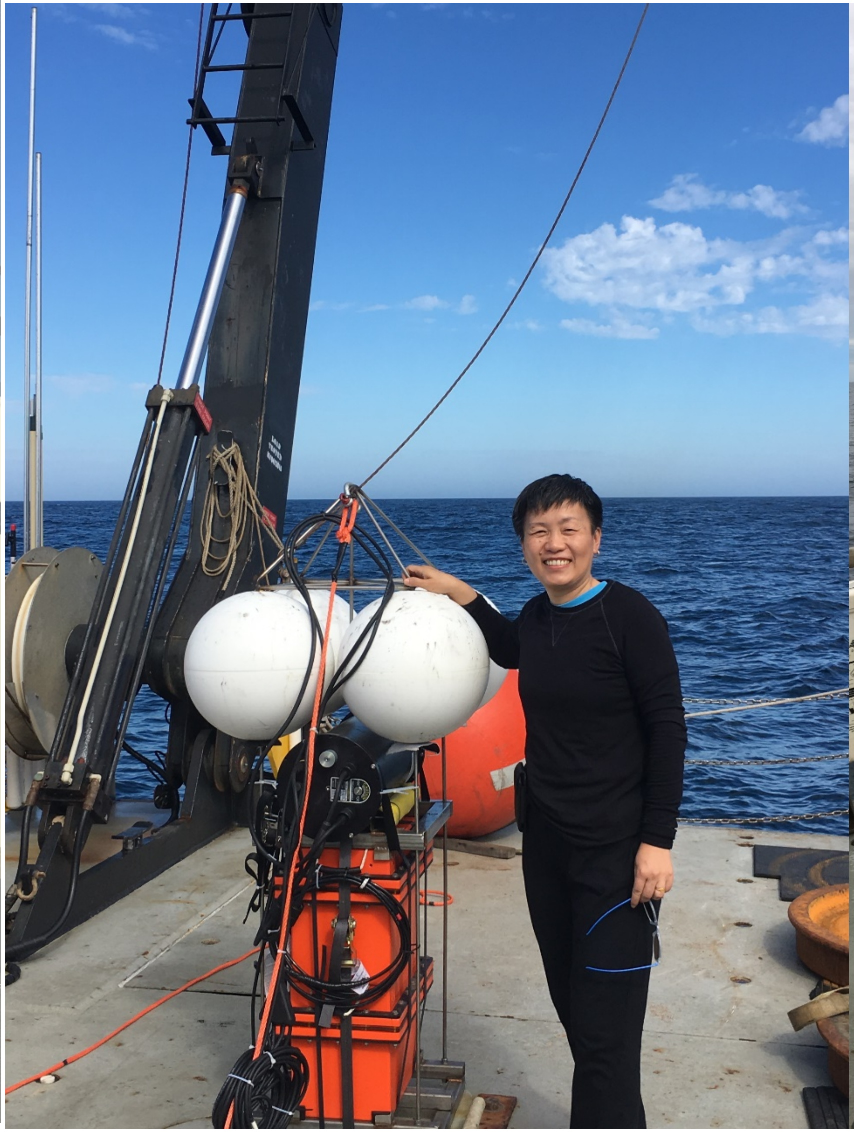
On 10 May 2014, *Nereus* was lost while exploring the Kermadec Trench at a depth of 9,900 meters (32,500 ft). Communications were cut off at around 2 p.m. local time, and debris retrieved later revealed that it imploded due to high pressure.

Robert Ballard: Ocean is the biggest natural history and human history museum.



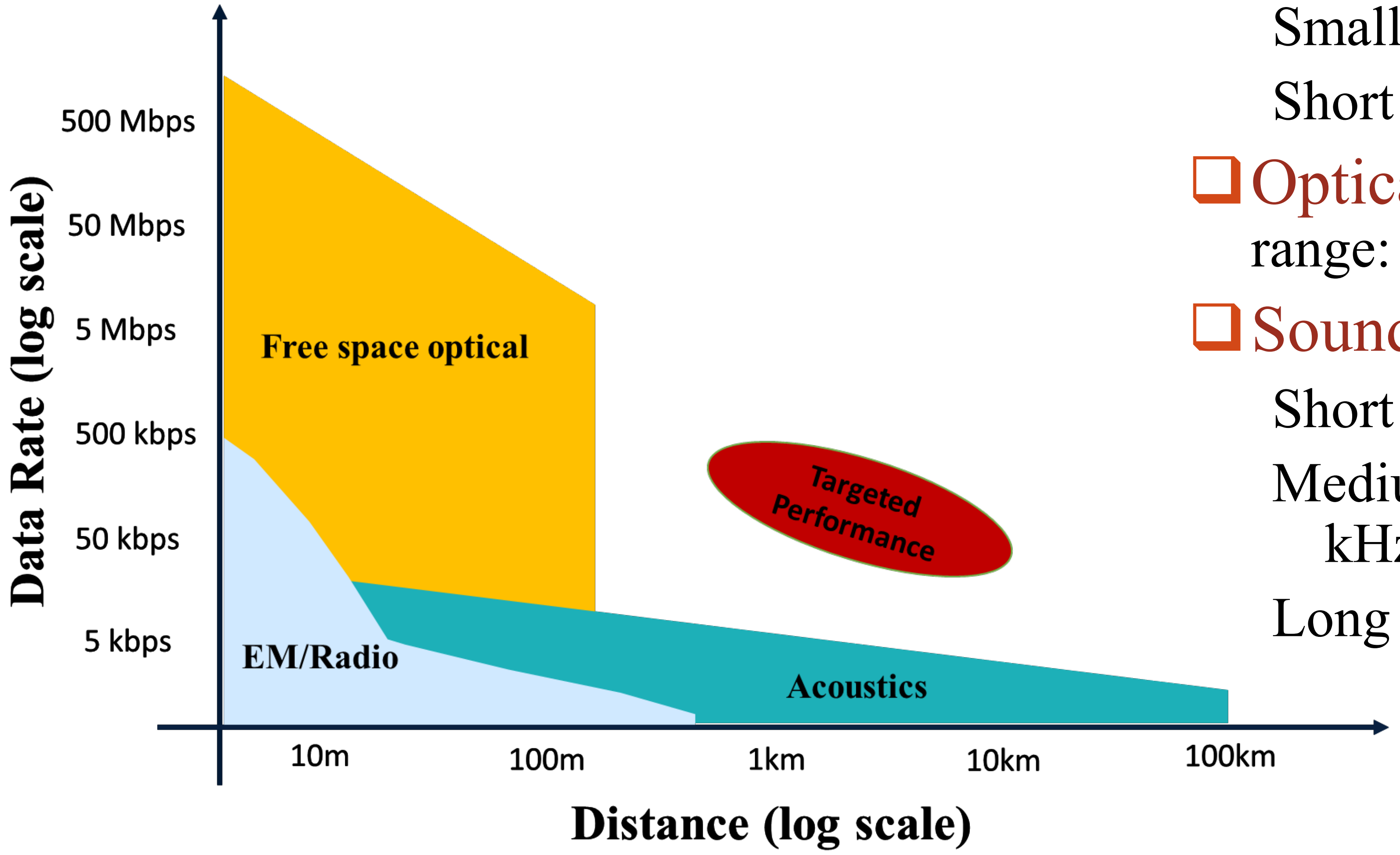
Field Experiments @ Atlantic Ocean 2017-18



Underwater Communication Means

- Radio Frequency (RF) does not work:

Limited BW (1MHz), very short range < 1 m



- Magneto-Inductive (MI) Communications:

  Small bandwidth (<500 kHz),

  Short range (~100 m)

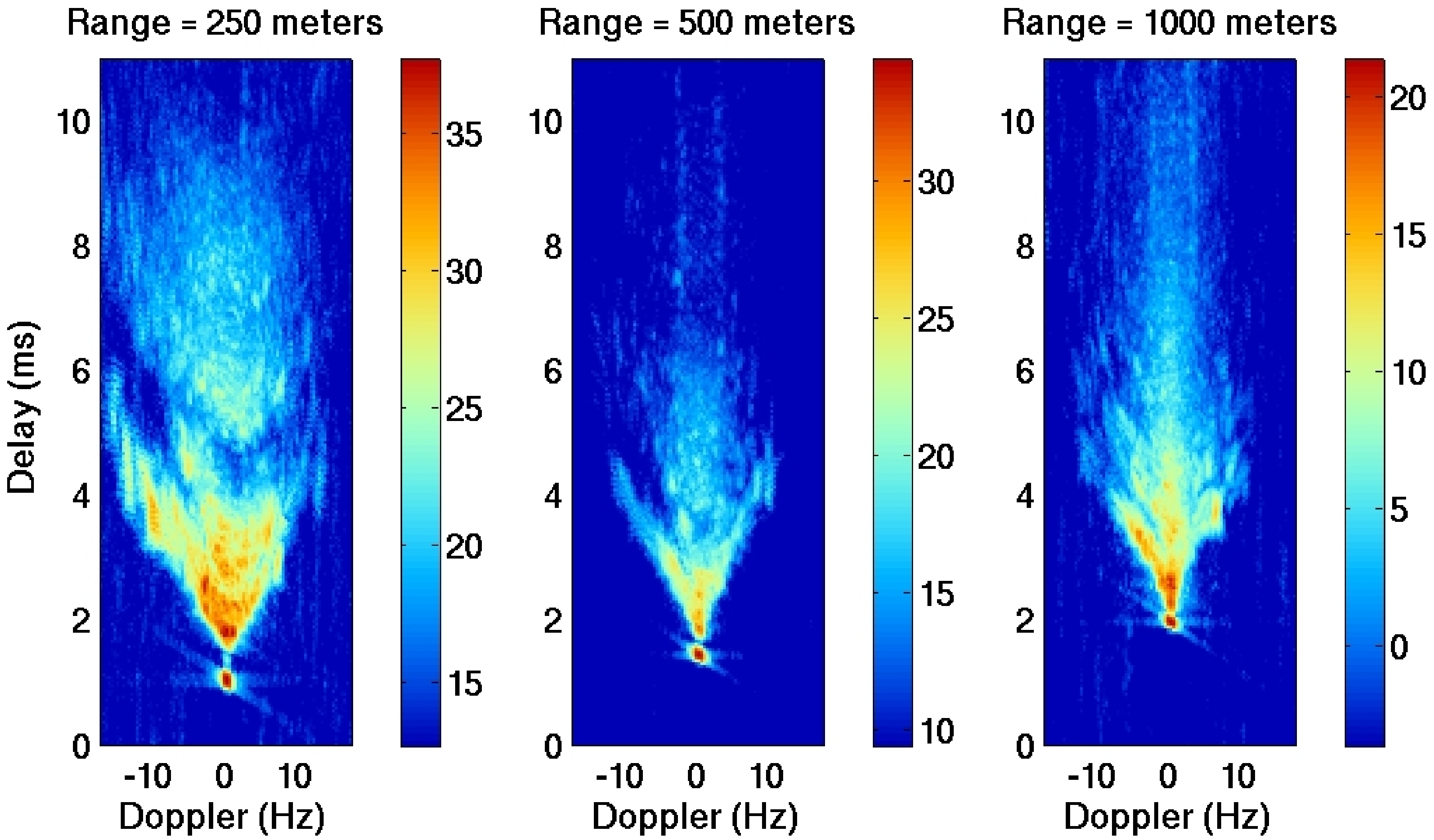
- Optical Beams: Large BW, short range: 20 m – 200 m
- Sound Propagation (AComm):

  Short range (<1 km): 300 kHz (HF)

  Medium range (1-10 km): 10 - 100 kHz (MF)

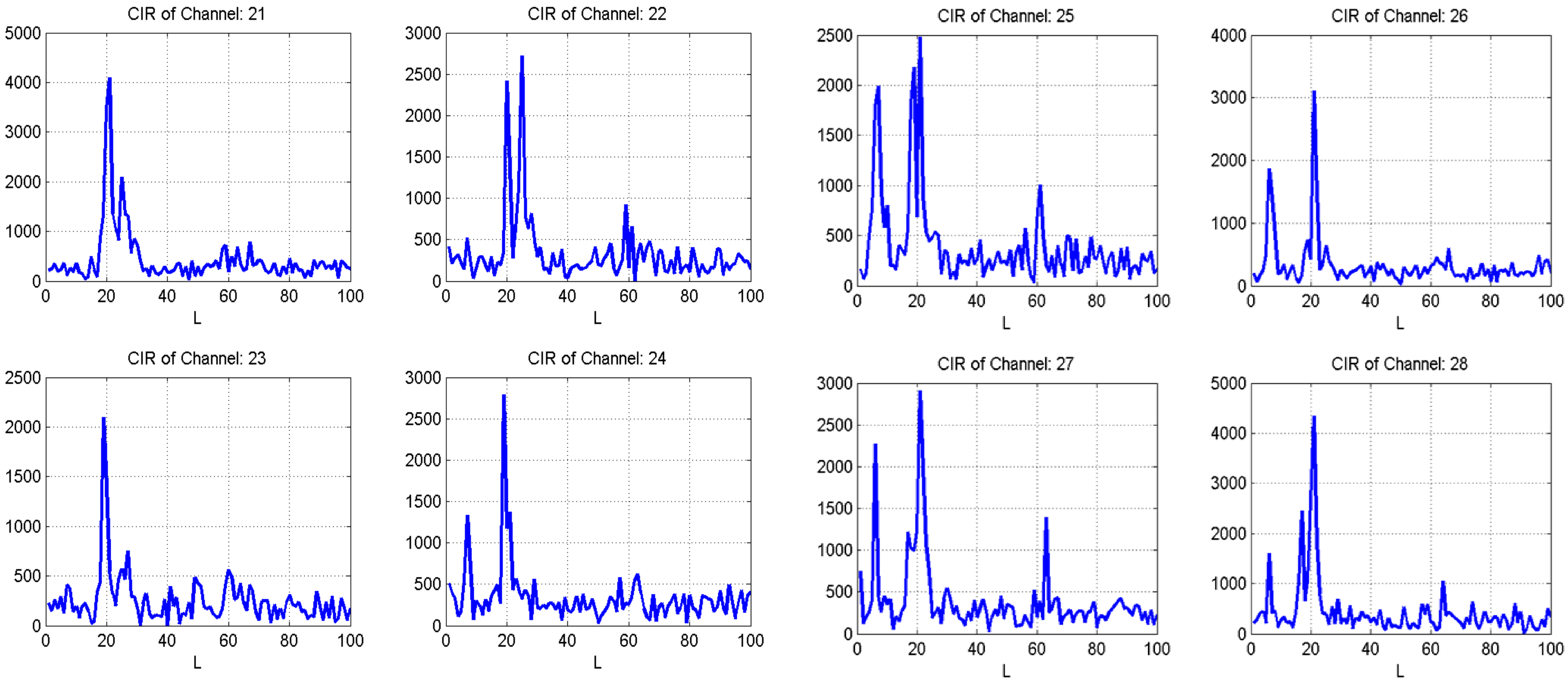
  Long range (1000 km): < 2 kHz (LF)

Acomm Multipath Channels



- Small BW:
  20 – 300 kHz
- Multipath:
  10 ms – 200 ms
- Doppler:
  5 – 20 Hz
- Doppler ratio:
  1e-4 ~ 1e-3

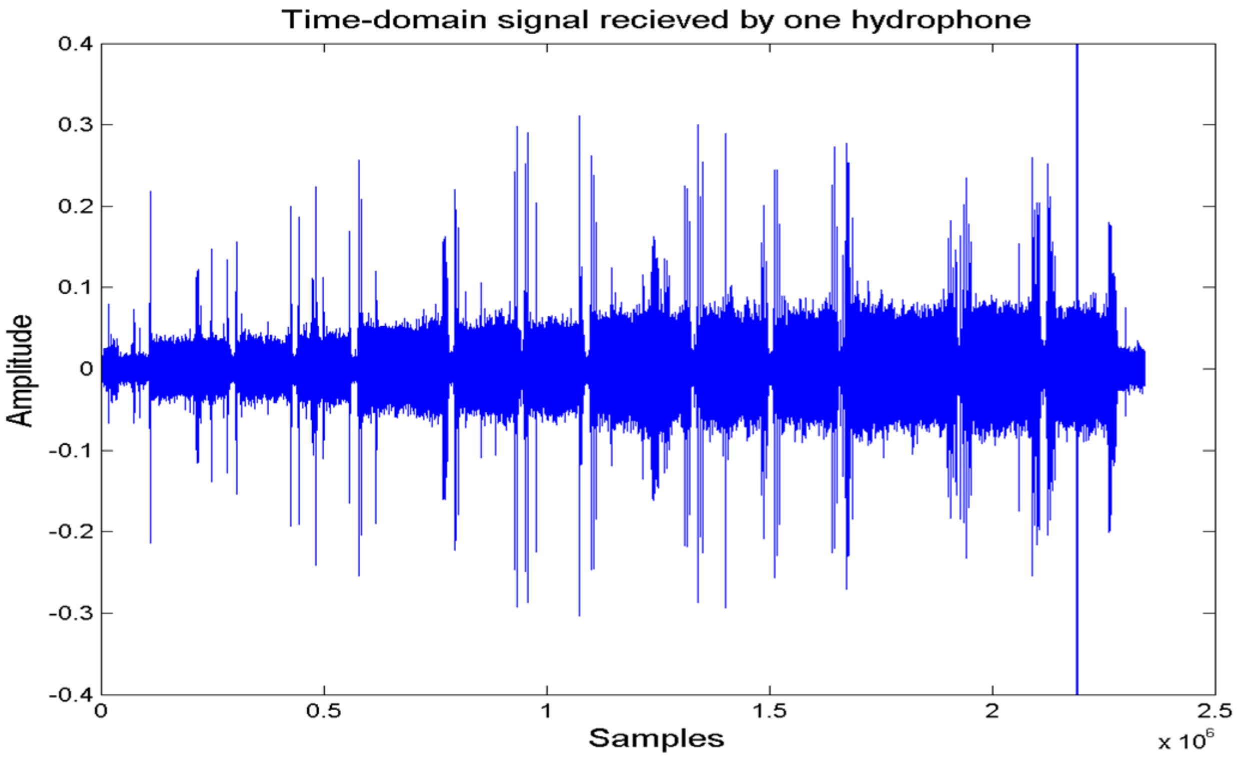
Inhomogeneous MIMO Channels

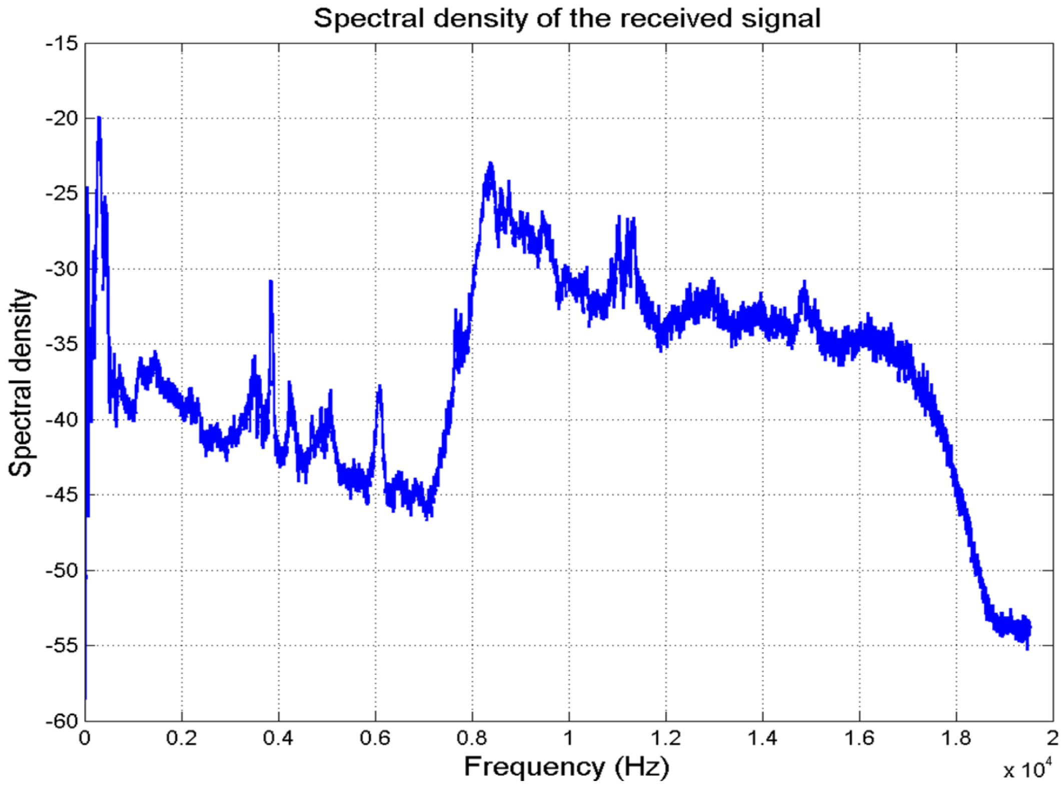


Received Signals @ SPACE08

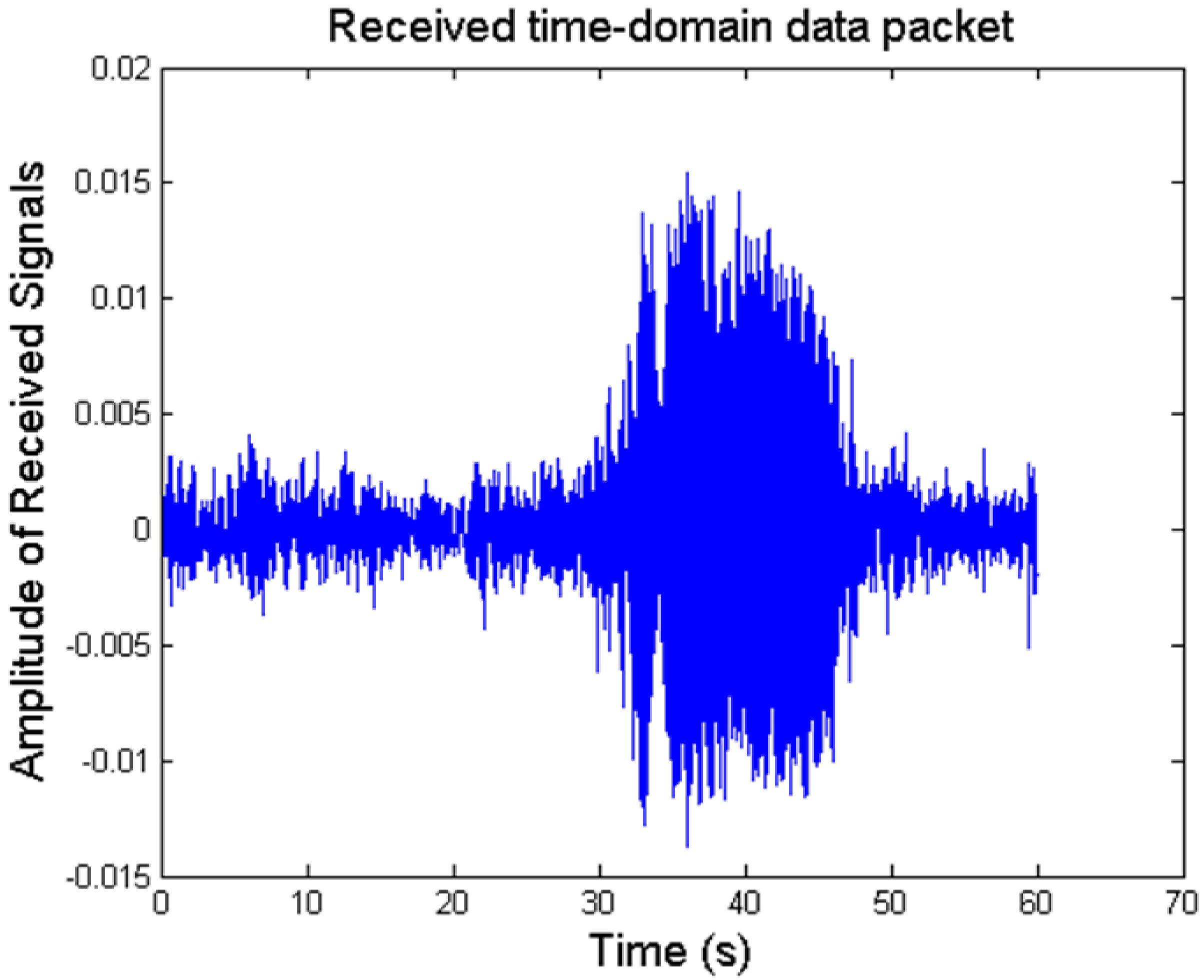
	Gap	1 Tx	2 Tx	3 Tx	4 Tx	Gap	Total
Symbols	20000	117000	130000	143000	155000	20000+937.5	2343750/4
Time	2.048s					2.048+0.096	60s

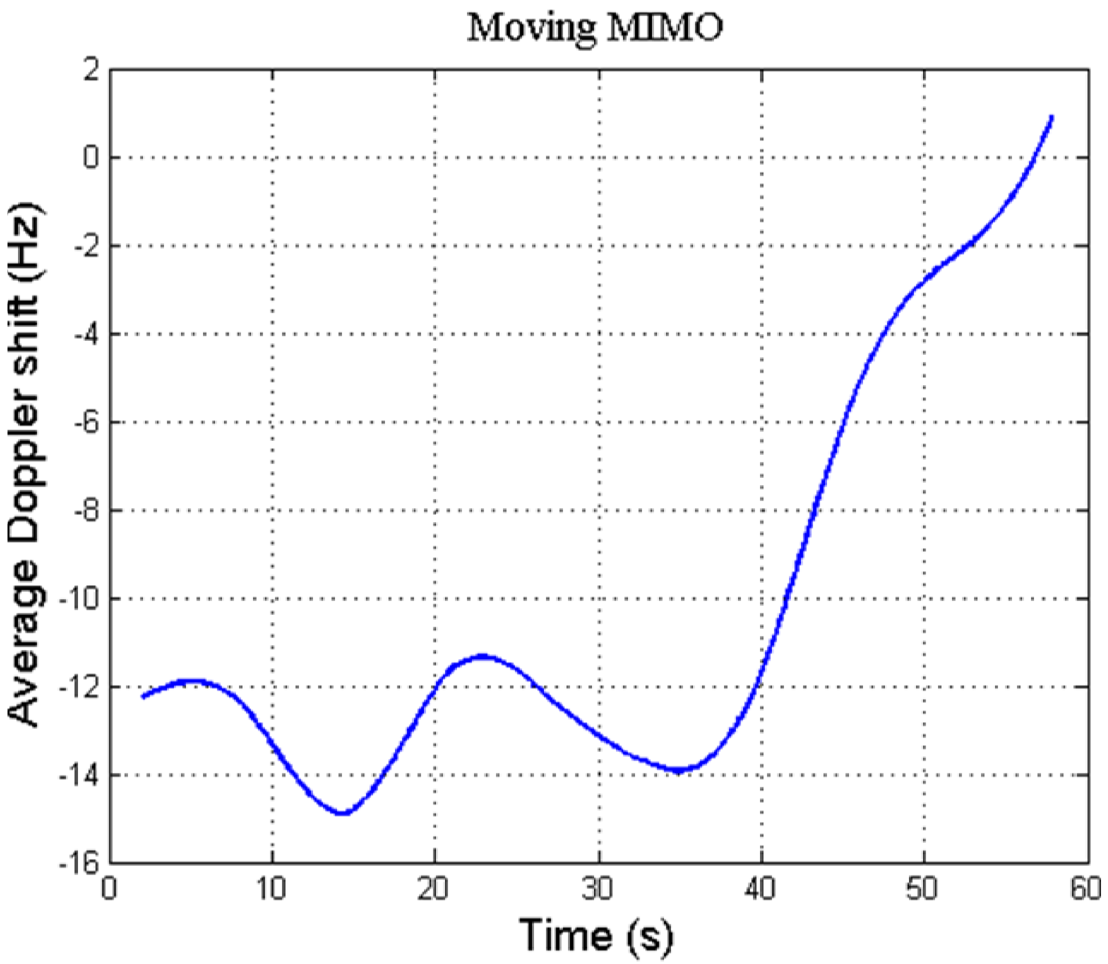
Carrier frequency	**13 kHz**
Bandwidth	9.765625 kHz
Error correction code	Rate-½ convolutional code [17, 13]





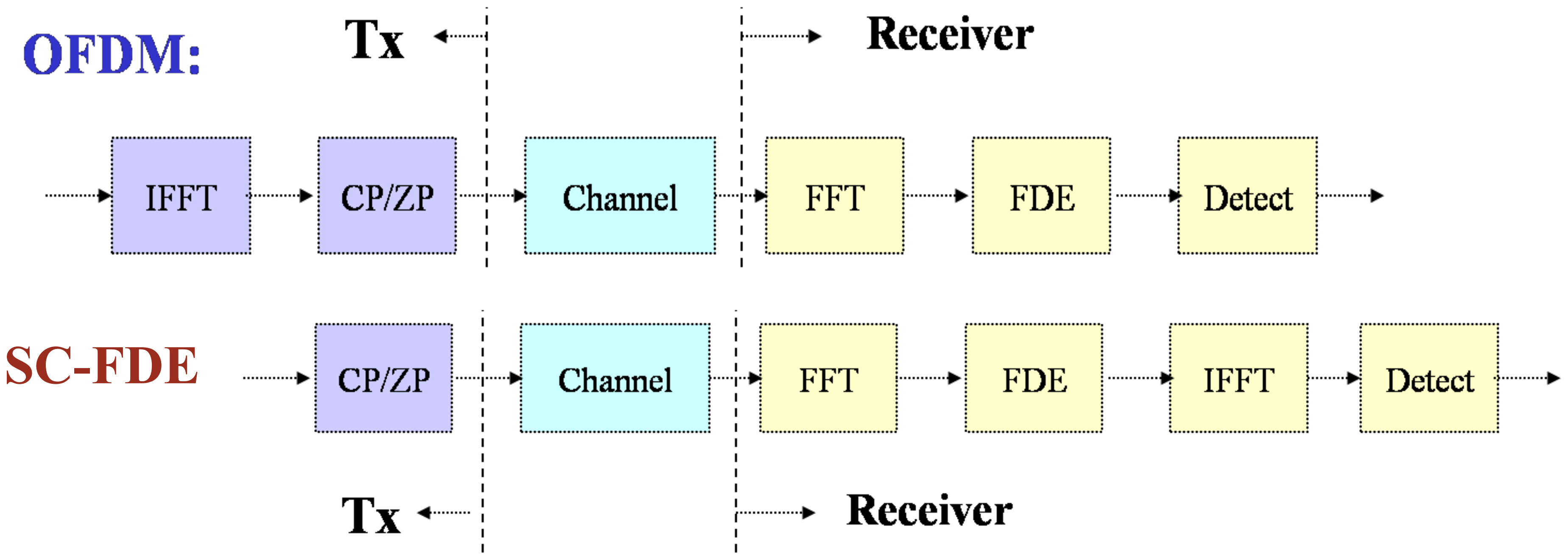
Moving MIMO Data





PHY-Layer Approaches

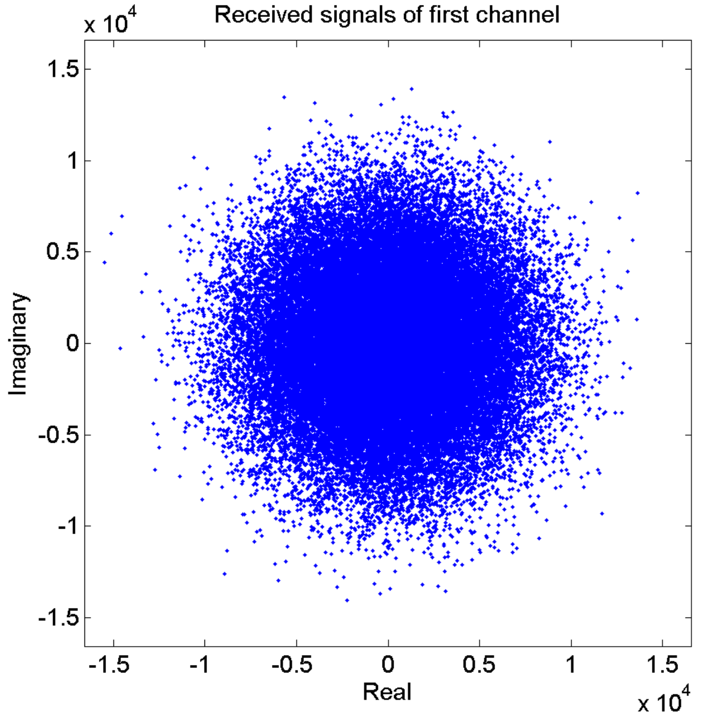
- MIMO Single-Carrier Time-Domain Turbo Equalization
- MIMO Single-Carrier Frequency-Domain Turbo Equalization
- MIMO OFDM with Turbo ICI Cancellation

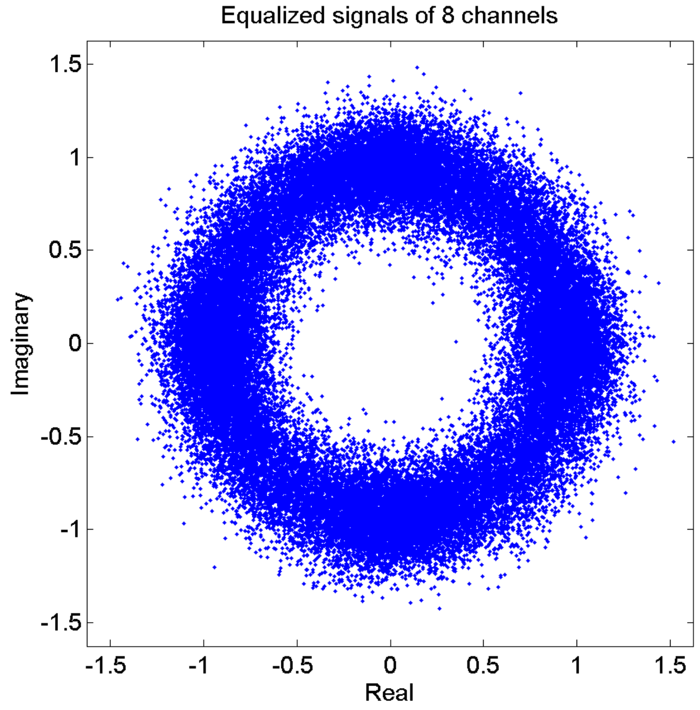


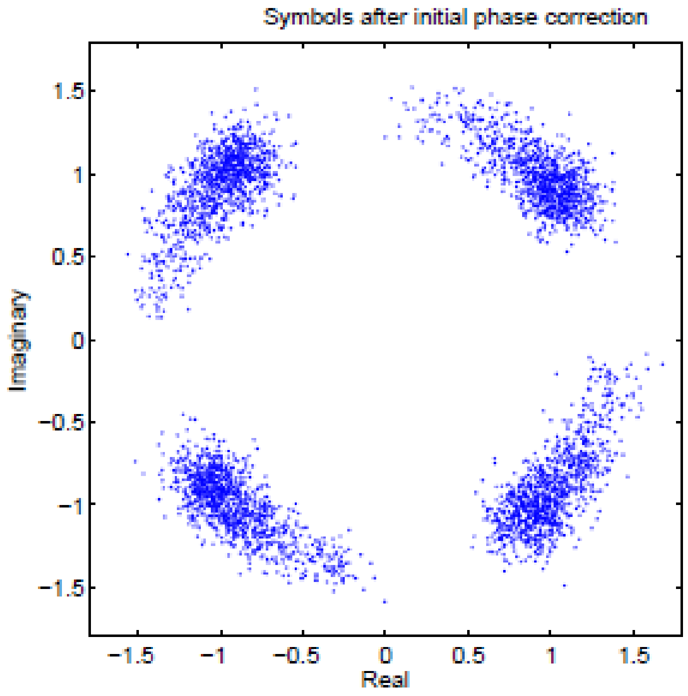
Figures adopted from Falconer's 1999 tutorial paper. Both are used for Cellular LTE.

SCM Acomm Challenges

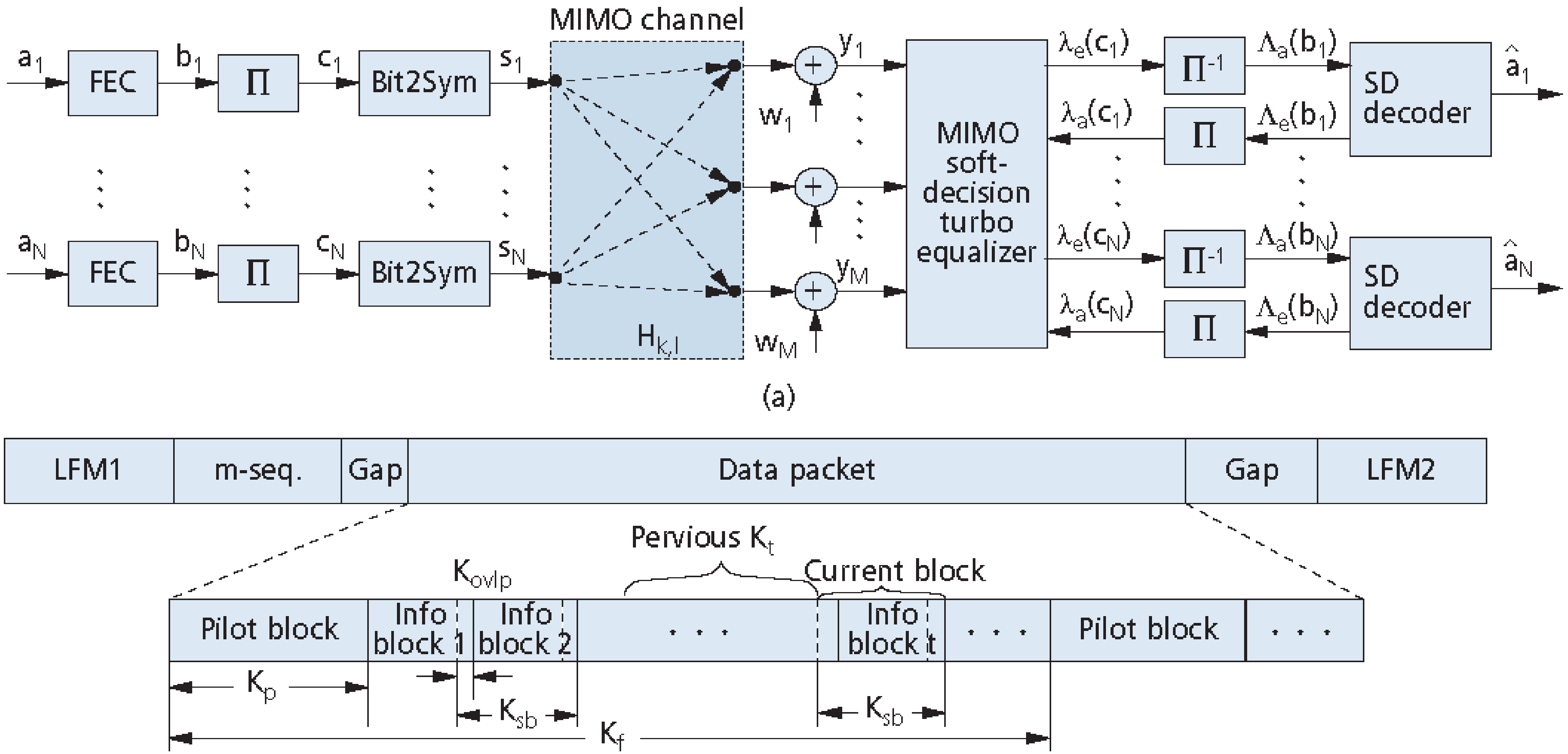
- Conventional Digital Receiver with Decision Feed-back Equalizer
- M. Stojanovic and J. Proakis: 1994 Coherent DFE w/ PLL





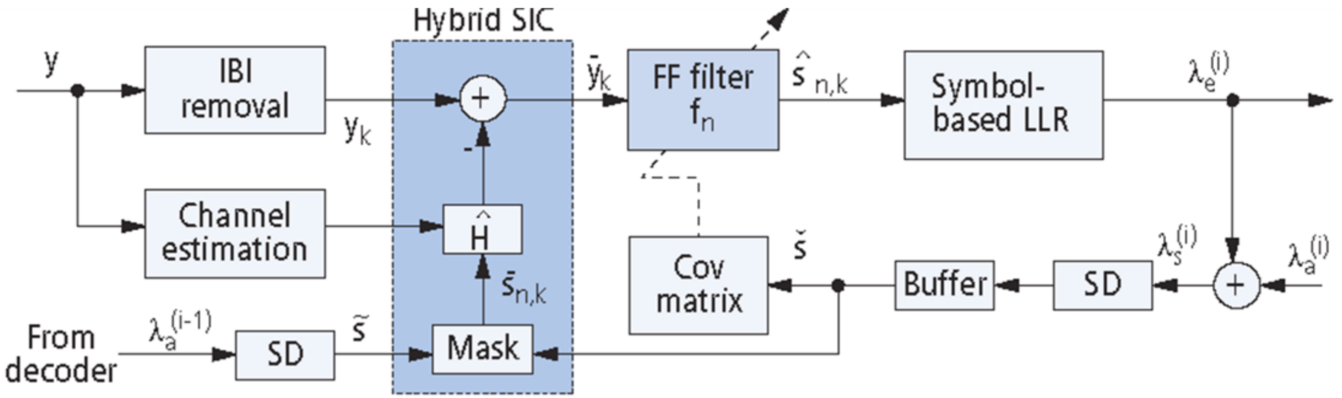


Architecture of MIMO Transceiver

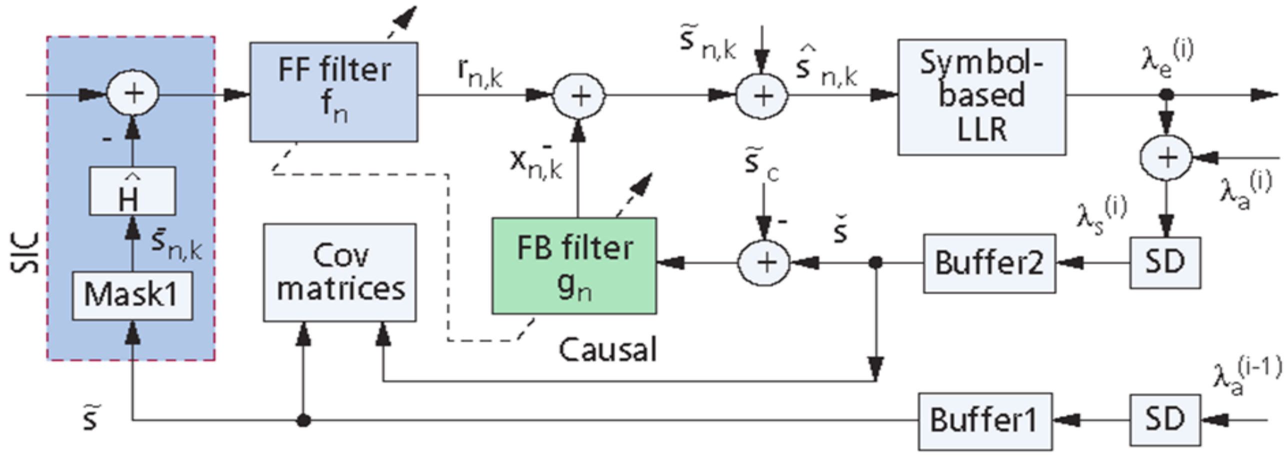


Y.R. Zheng, J. Wu, and C. Xiao, "Turbo Equalization for Underwater Acoustic Communications," IEEE Commun. Mag., vol. 53, no. 11, pp. 79-87, Nov. 2015.

Time-Domain Turbo Equalizers



Turbo Linear Equalizer



Turbo Soft-Decision Feedback Equalizer

$$\mathbf{y}_k = \mathbf{H}\mathbf{s}_{n,k} + \mathbf{w}_k$$

$$\hat{s}_{n,k} = \mathbf{f}_n^h(\mathbf{y}_k - \mathbf{H}\tilde{\mathbf{s}}_{n,k})$$

$$\mathbf{H} = \begin{bmatrix} h_{L-1} & \cdots & h_0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & h_{L-1} & \cdots & h_0 \end{bmatrix}$$

$$\hat{s}_{n,k} = \left(\mathbf{f}_{n,k}^h \mathbf{H}\mathbf{e}_k\right) s_{n,k} + \eta_{n,k},$$

$$\mathbf{f}_{n,k} = (\mathbf{H}\mathbf{V}_k\mathbf{H}^h + \sigma_w^2 \mathbf{I}_K)^{-1}\mathbf{H}\mathbf{e}_k$$

$$\mathbf{V}_k = \begin{bmatrix} 0 & \ddots & 0 & \cdots & & \\ \cdots & 0 & v_{k-1} & 0 & \cdots & \\ & \cdots & 0 & 1 & 0 & \cdots \\ & & \cdots & 0 & v_{k+1} & 0 \\ & & & \cdots & 0 & \ddots \end{bmatrix}$$

Soft-Decision Decoding & Equalization

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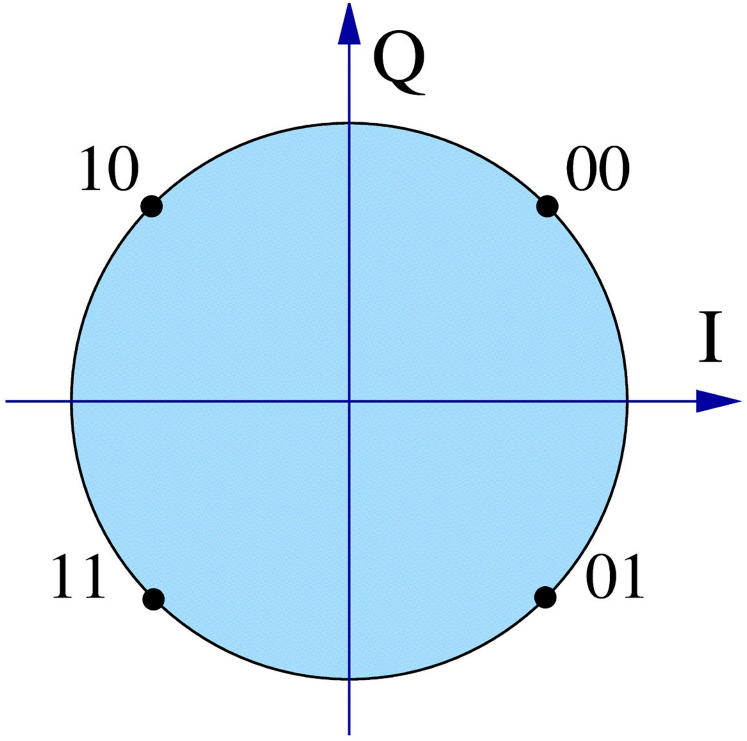
- Variance: $v_k = \sum_{\alpha_m \in S} |\alpha_m - \bar{s}_k|^2 P(s_k = \alpha_m)$



- Extrinsic Log-likelihood ratio (LLR)

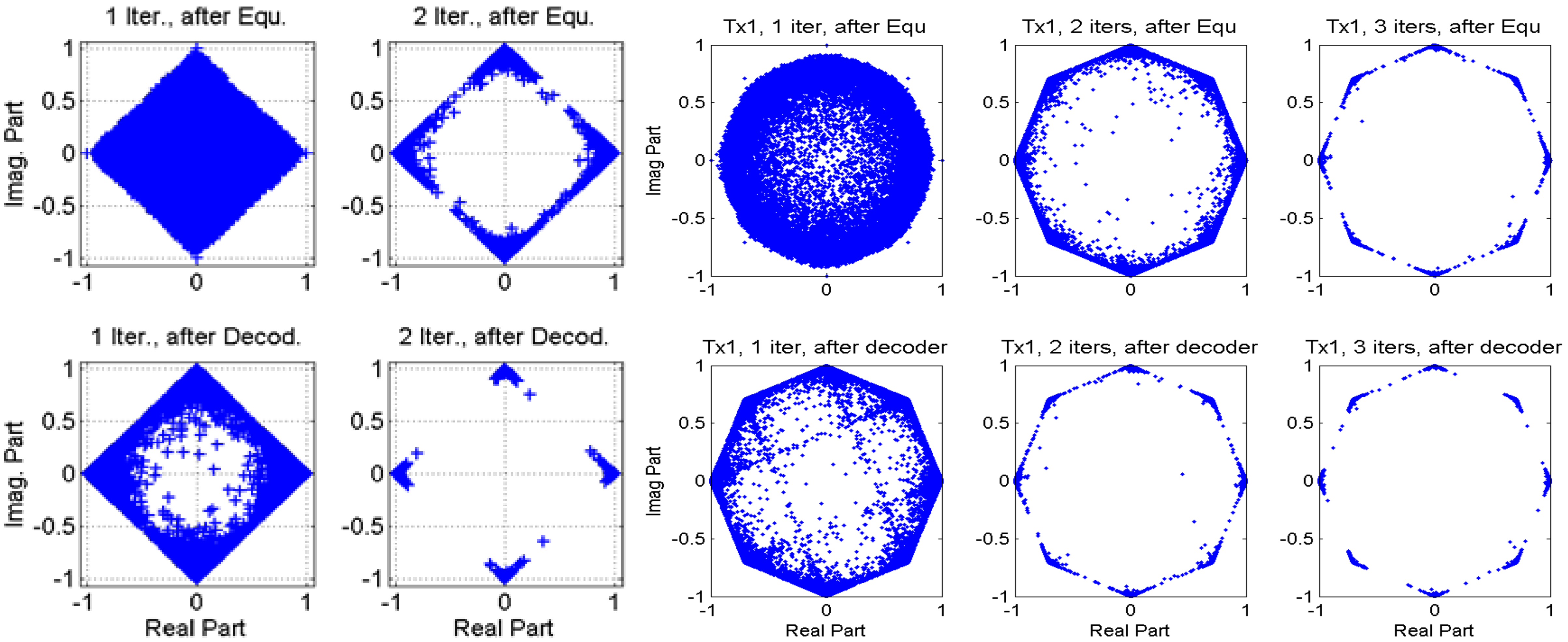
$$\lambda_e(c_{k,q}) = \ln \frac{\sum_{\alpha_m : c_{k,q}=0} p(\hat{s}_k | \alpha_m) \prod_{\forall q', q' \neq q} P(c_{k,q'})}{\sum_{\alpha_m : c_{k,q}=1} p(\hat{s}_k | \alpha_m) \prod_{\forall q', q' \neq q} P(c_{k,q'})}$$

- Soft Symbol Mapping

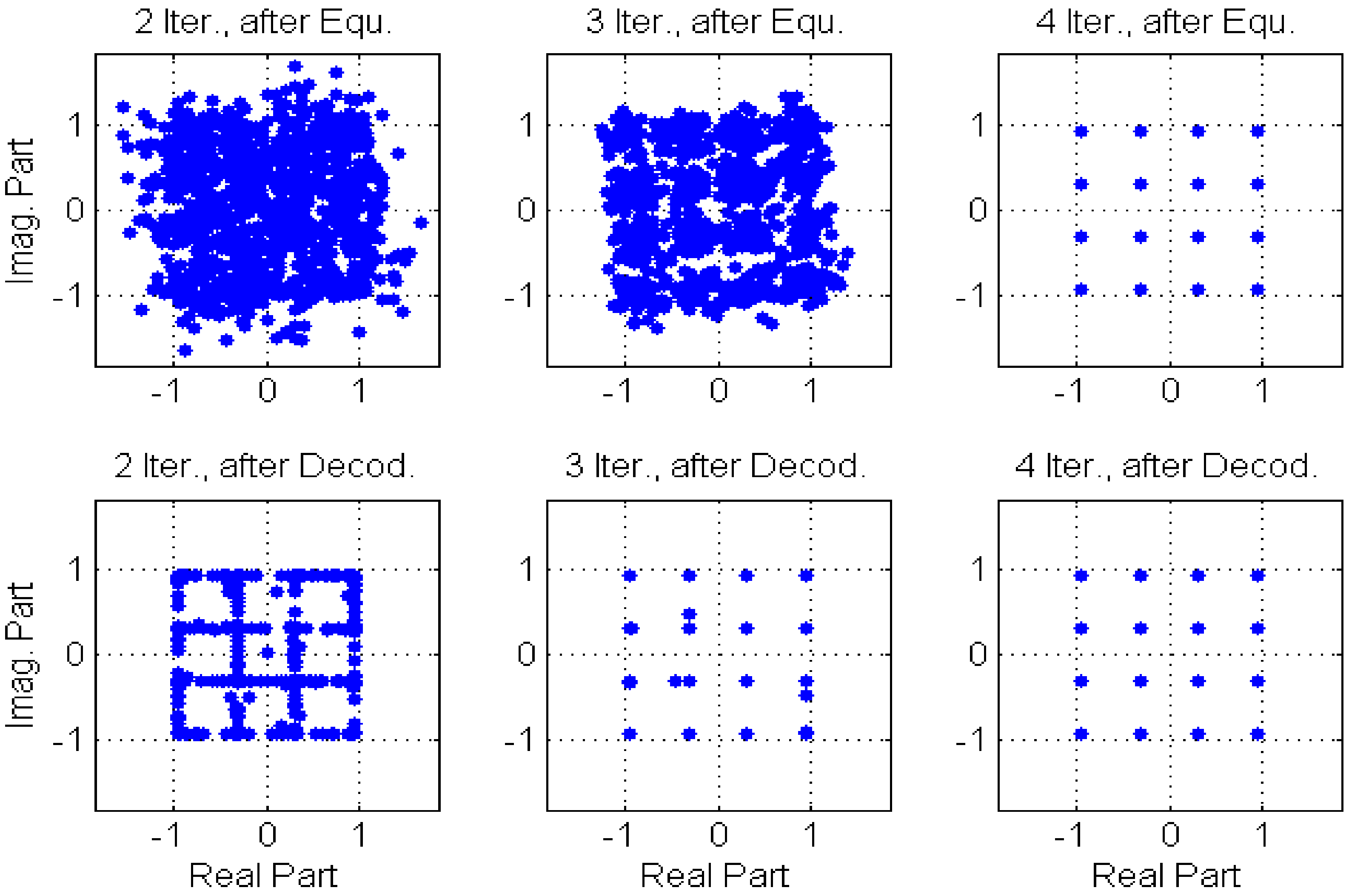
$$\bar{s}_k = E\left[s_k | \{\lambda_a(c_{k,q})\}_{q=1}^{Q} \right] = \sum_{\alpha_m \in S} \alpha_m P(s_k = \alpha_m)$$

$$P(s_k = \alpha_m) = \prod_{q=1}^{Q} \frac{1}{2} \left(1 + \tilde{s}_{m,q} \tanh\left(\lambda_a(c_{k,q})/2\right)\right), \qquad \tilde{s}_{m,q} = \begin{cases} +1 & \text{if } s_{m,q} = 0 \\ -1 & \text{if } s_{m,q} = 1. \end{cases}$$

Time-Domain Turbo Equalizers



High Order Modulation



- ❑ Symbol rate*5
- ❑ 16 QAM
  - → 4 bits/symbol
- ❑ 4Tx elements
  - → 4 data streams
- ❑ No CP/ZP

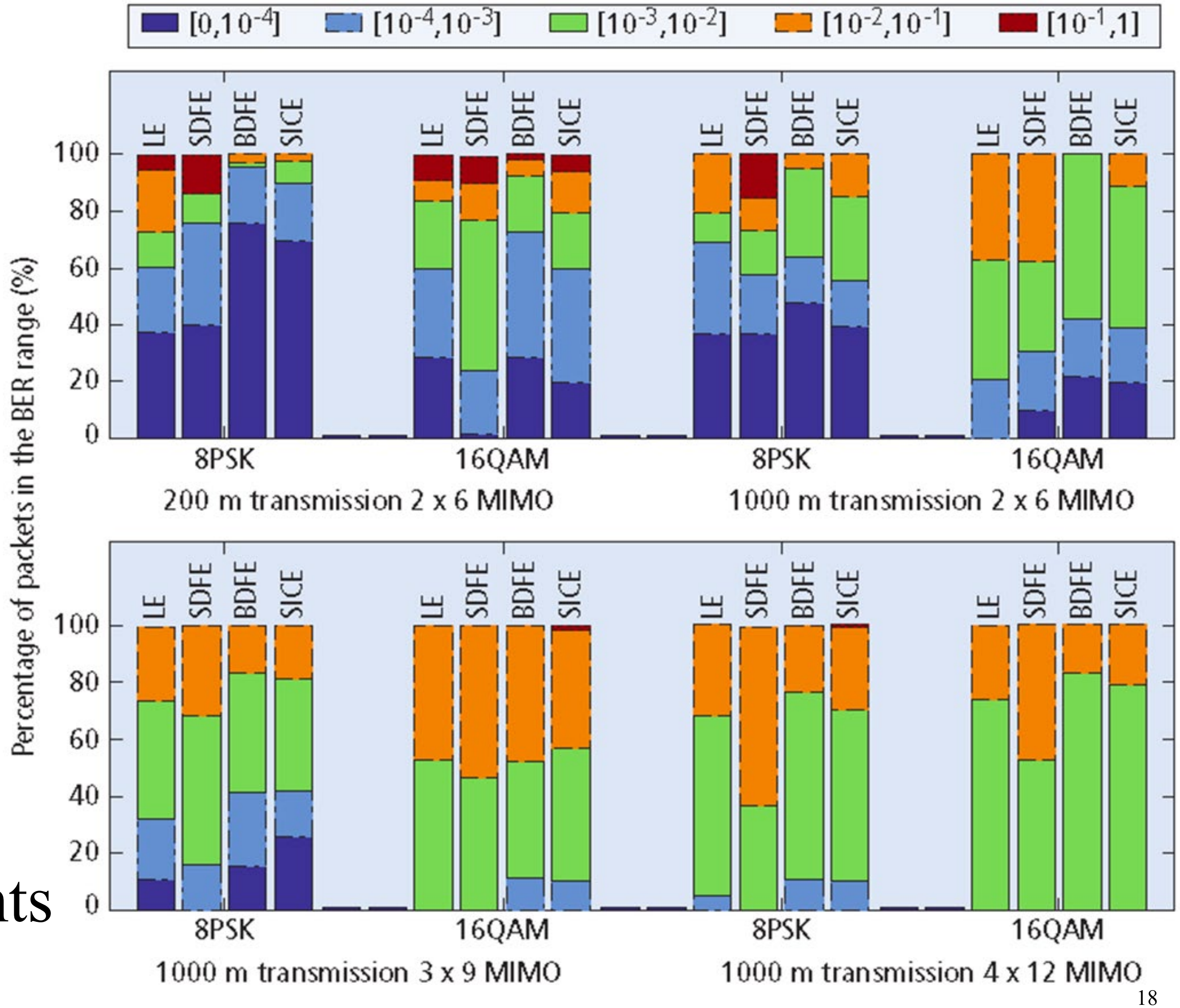
→ 85% efficiency

→ 80x information bit rate

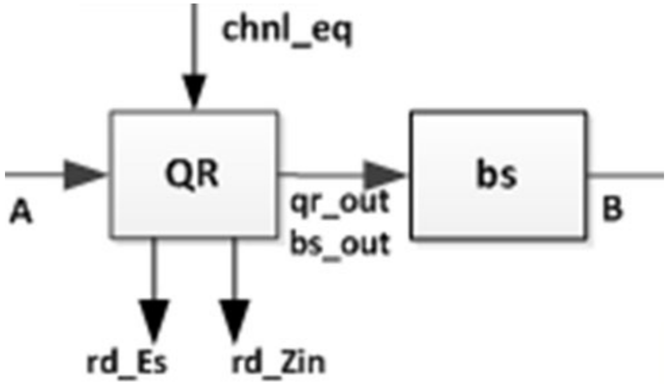
→ Improved detection

Underwater Acomm Algorithms

- TD Methods:
  - TD Linear Equalizer
  - TD Block DFE, SDFE and SICE
  - Bi-Directional SDFE
  - Adaptive Channel Estimation
  - Direct-Adaption Turbo Equalizer
- FD Turbo Equalizers:
  - FD LE + Phase Correction
  - FDE-FDDF and FDE-TDDF
  - TDE-FDDF
- 12 algo tested over 20 experiments



Equalizer Implementation



$$\hat{\mathbf{s}}_{n,k} = (\mathbf{H}_{ek}\mathbf{H}_{ek}^h + \sigma_w^2 \mathbf{I}_K)^{-1}\mathbf{H}_{ek}\mathbf{y}_k$$

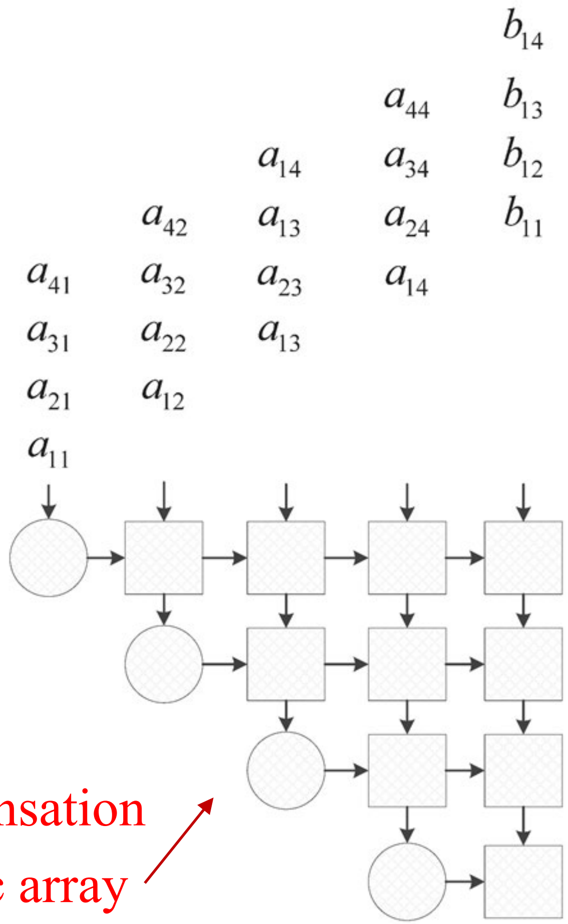
$$\mathbf{AX} = \mathbf{B} \quad \rightarrow \quad \mathbf{RX} = \mathbf{Q}^h\mathbf{B} = \mathbf{z}$$

$$s_n = \frac{1}{r_{nn}}\left(z_n - \sum_{j=n+1}^{N} r_{n,j}s_j\right), \quad n = N, \cdots, 2, 1$$

Givens rotation for 4-by-4 matrix

$$\mathbf{G}_1 = \begin{bmatrix} C_1 & S_1 & 0 & 0 \\ -S_1^h & C_1^h & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

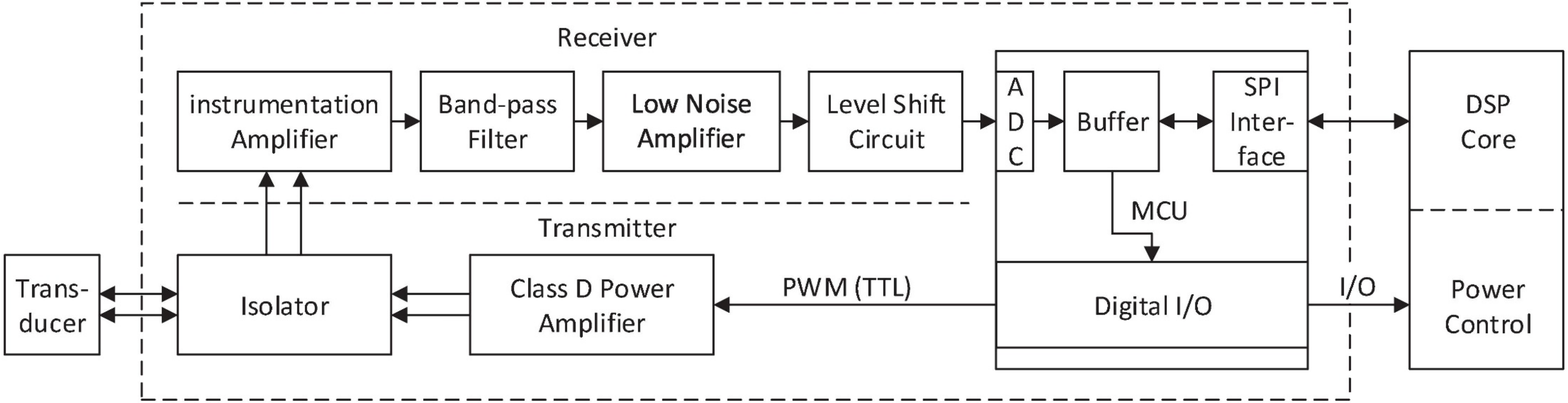
$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ 0 & r_{22} & r_{23} & r_{24} \\ 0 & 0 & r_{33} & r_{34} \\ 0 & 0 & 0 & r_{44} \end{bmatrix}$$

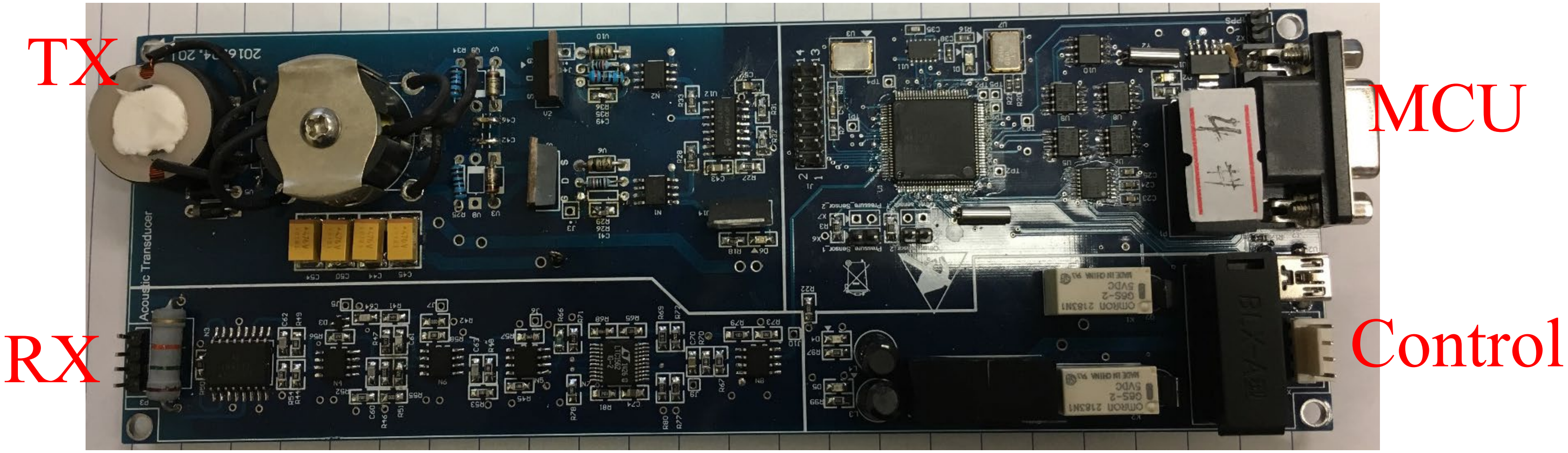


QR decompensation by 2D systolic array

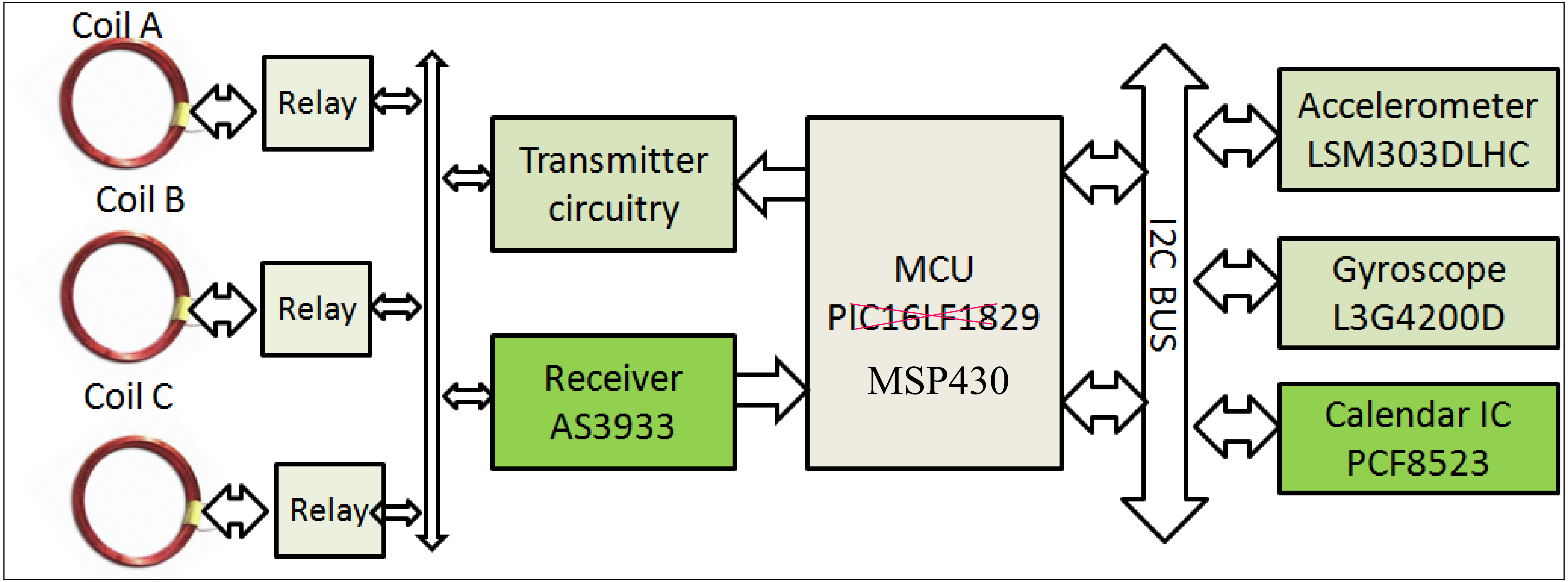
B. Han, Z. Yang, and **Y. R. Zheng**, "FPGA Implementation of QR Decomposition for MIMO-OFDM Using Four CORDIC Cores," IEEE ICC 2013, Budapest, Hungary, June 9-13, 2013. pp. 1-6.

Hardware Implementation w/ TI MCU



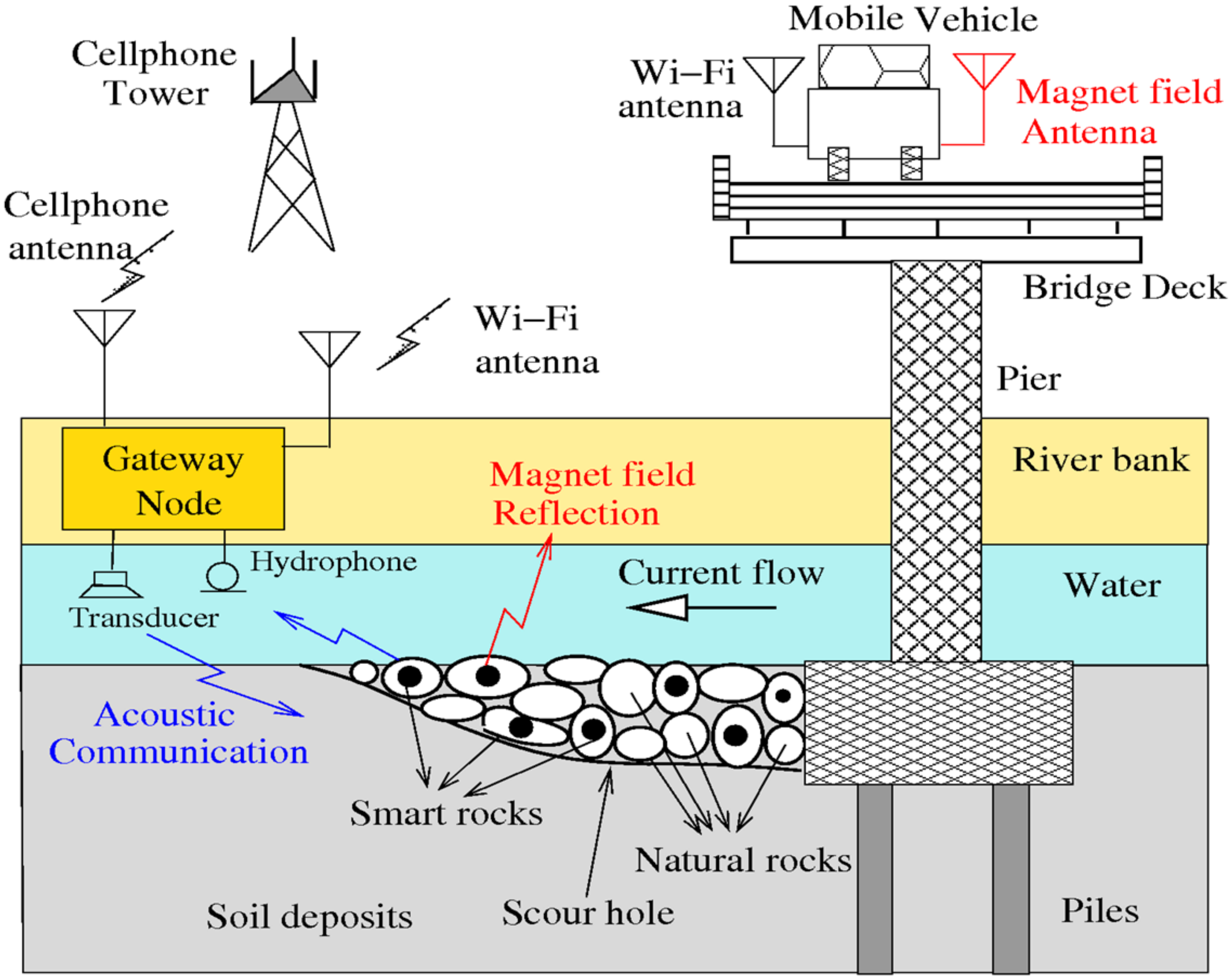


MI Communication System



Version 3 MI system w/ 3-D antenna coils

Underwater Internet of Things



Injectable Acoustic Fish Tracking Tag

Bridge Scour Monitoring

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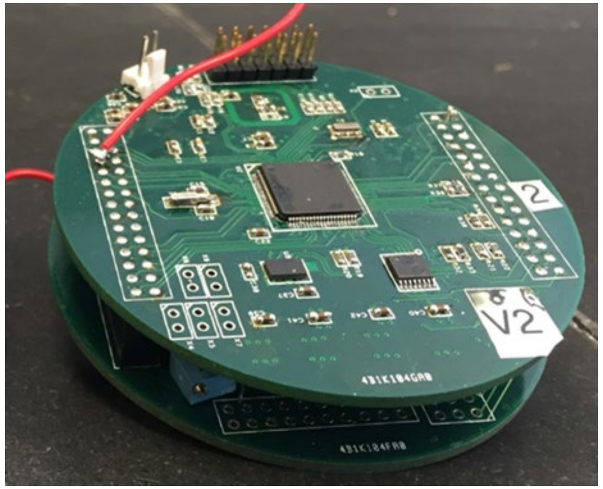

Rock shells weigh 50 – 200 lb

Bridge Tests

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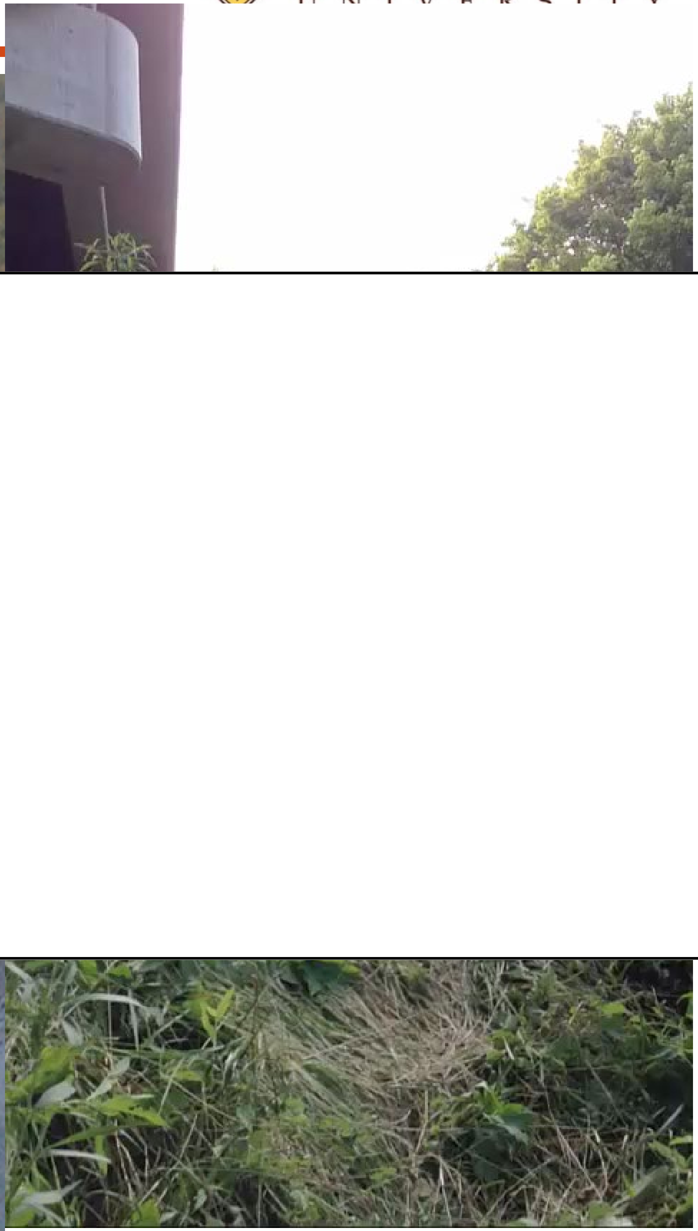
Gasconade River, July 2013

Rubidoux River, May 2018



Conclusion and Future Work

- Underwater wireless communication is a lot harder than terrestrial communication;
- Three means in underwater wireless communication:
  - Ultrasound (acoustic) communications (Acomm);
  - Optical Communications;
  - Magneto-Inductive (MI) Communications.
- Future work:
  - Hardware Implementation and applications: IoT, IoUT
  - Innovative network protocols and secure communication.