# Underwater Wireless Communications: Modem Design and Implementation

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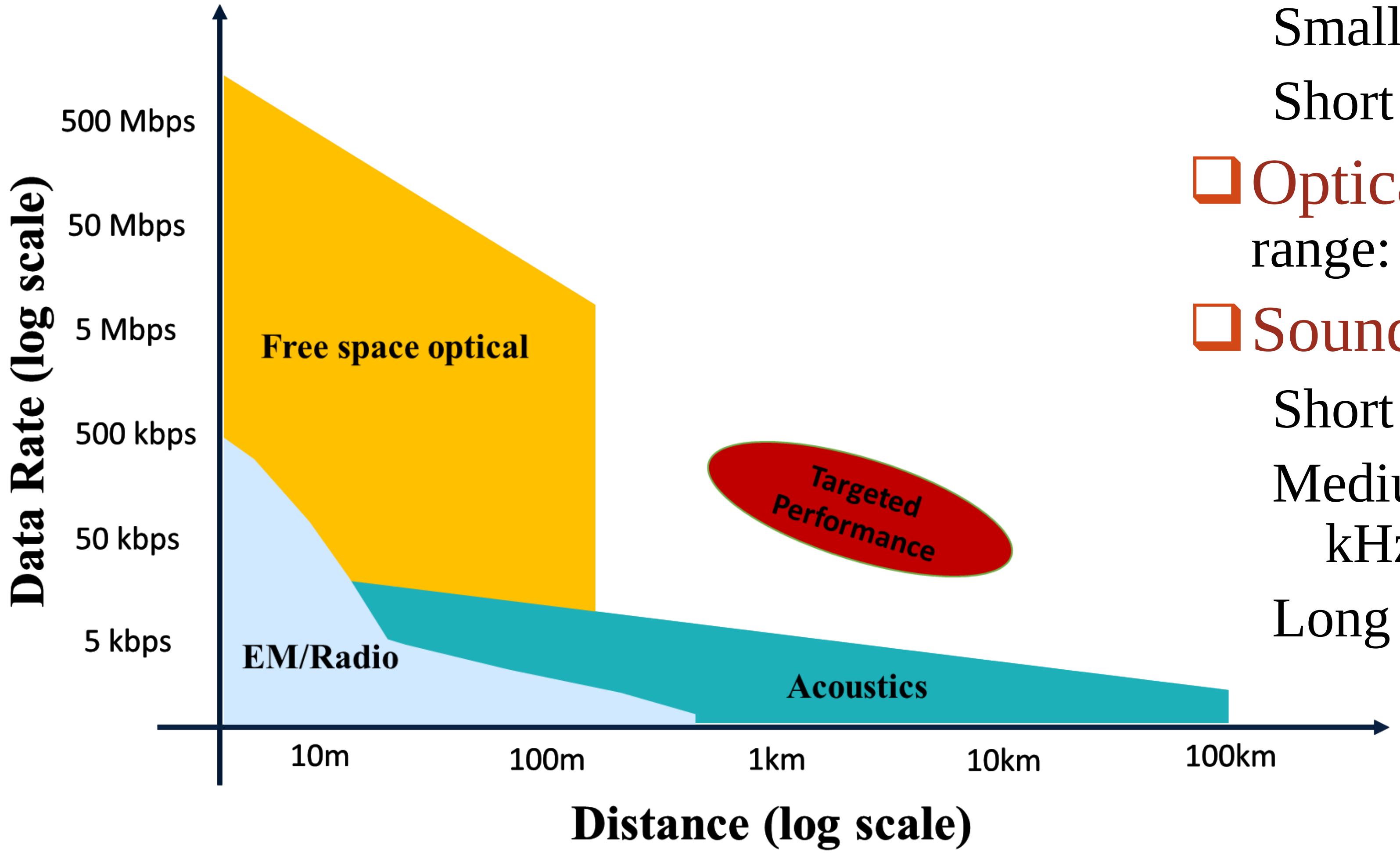
# Underwater Communication Means

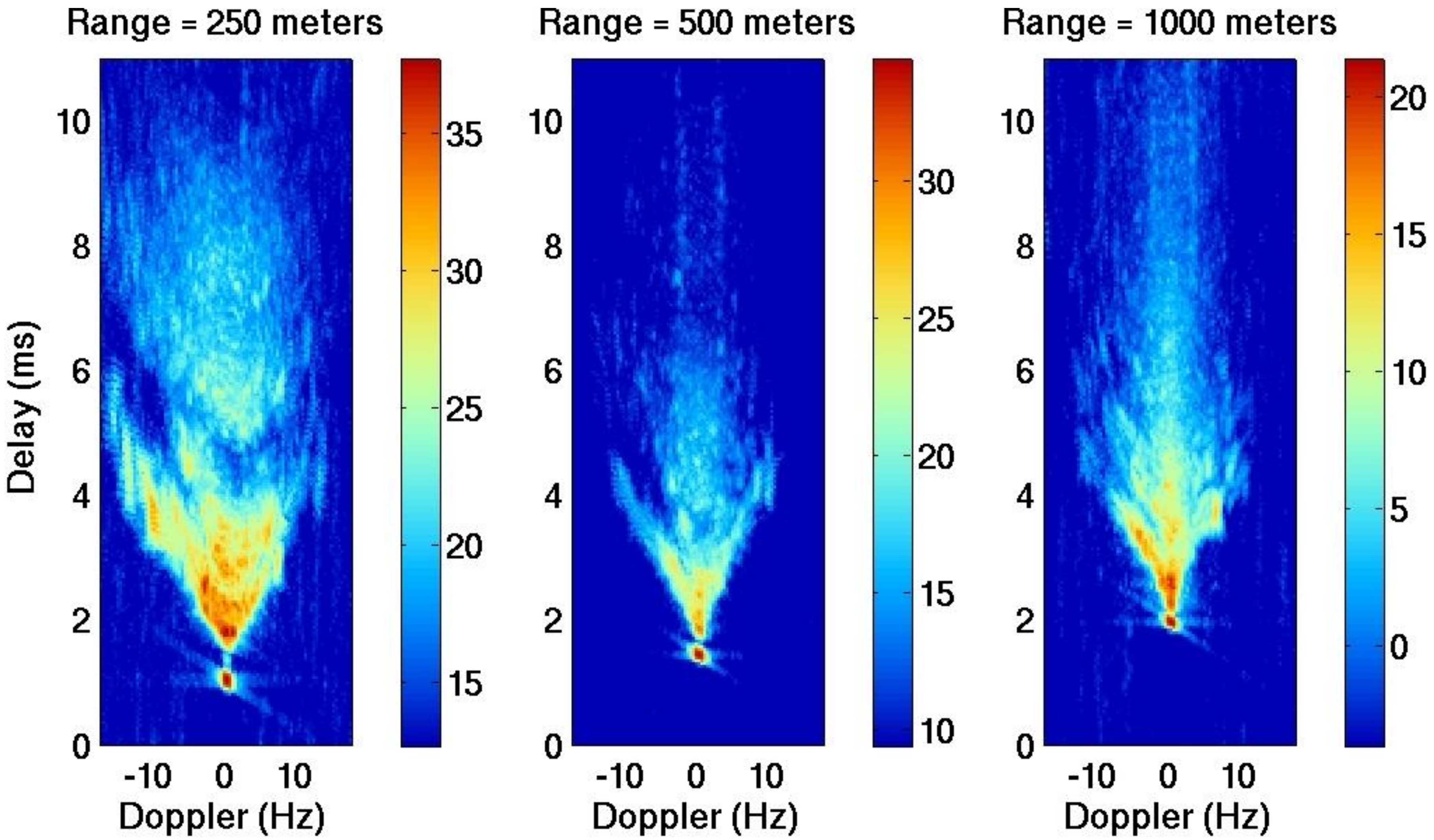
- **Radio Frequency (RF) does not work:**

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)

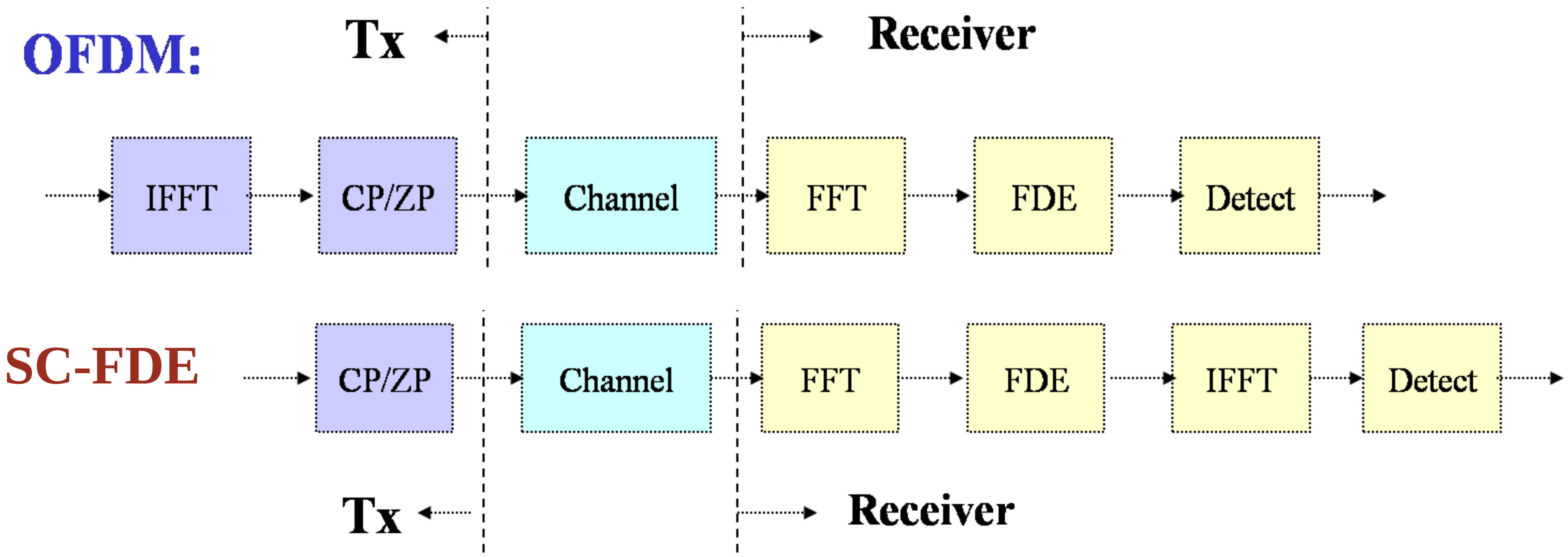
# Acomm Multipath Channels




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

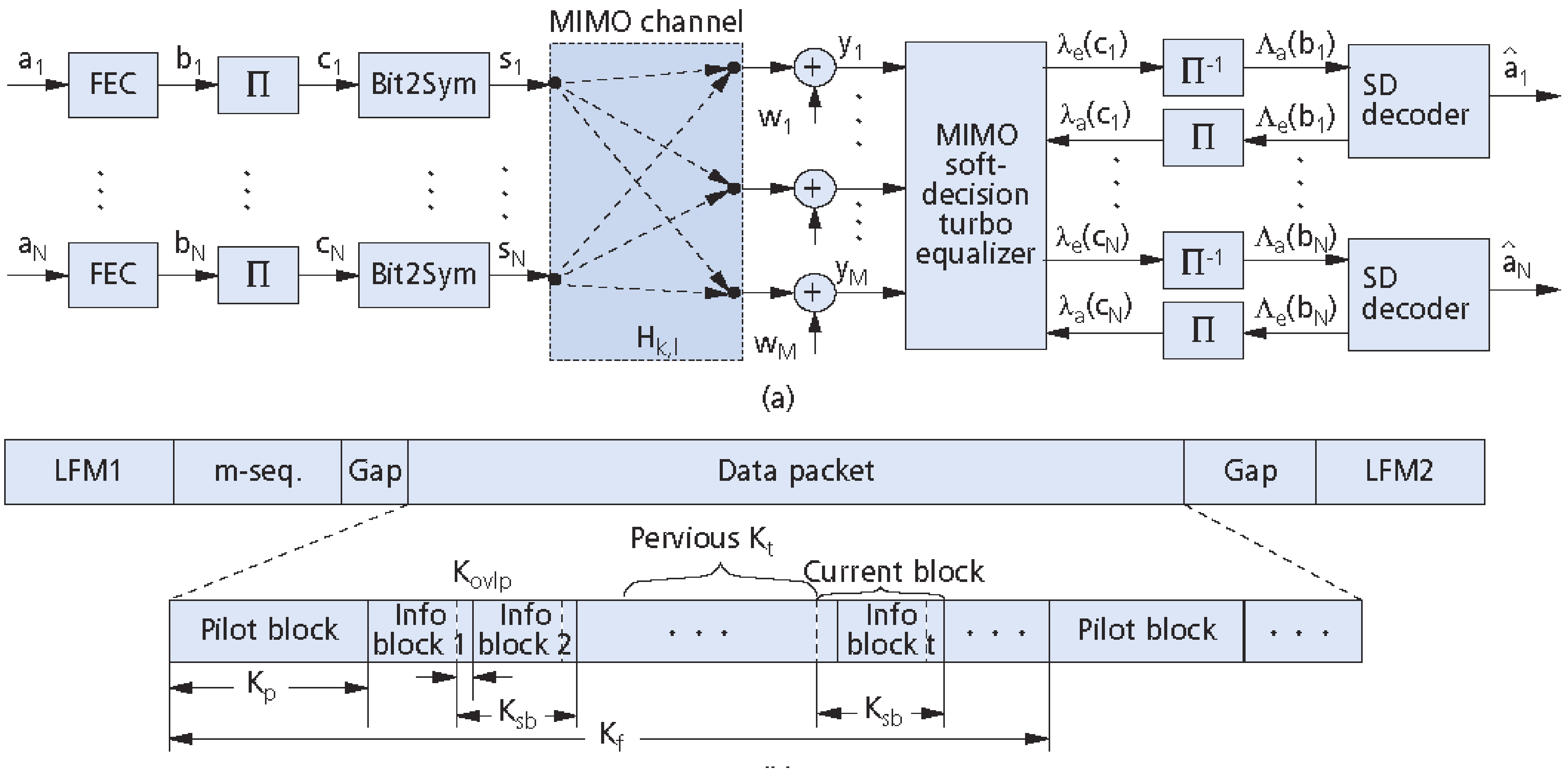
# PHY-Layer Acomm Approaches

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



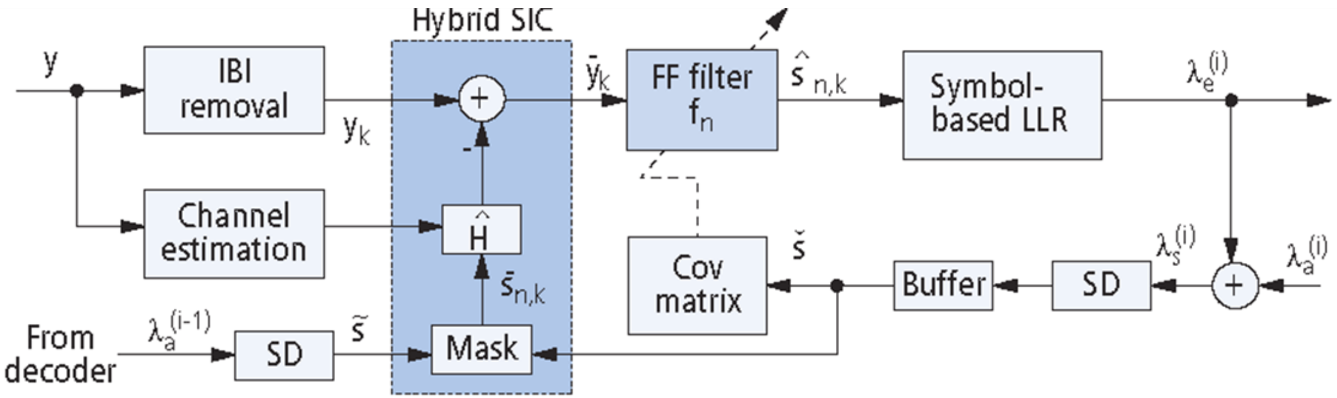

Figures adopted from Falconer's 1999 tutorial paper. Both are used for Cellular LTE.

# Architecture of MIMO Transceiver

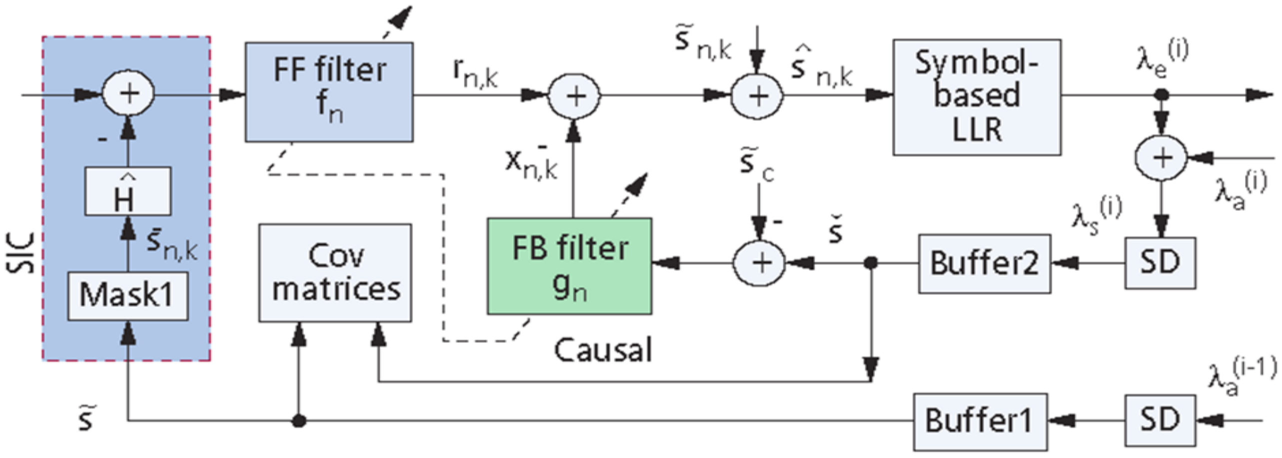



**Y.R. Zheng**, J. Wu, and C. Xiao, "Turbo Equalization for Underwater Acoustic Communications," IEEE Commun. Mag., vol. 53, no. 11, pp. 79-87, Nov. 2015.

# Time-Domain Turbo Equalizers




Turbo Linear Equalizer




Turbo Soft-Decision Feedback Equalizer

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

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

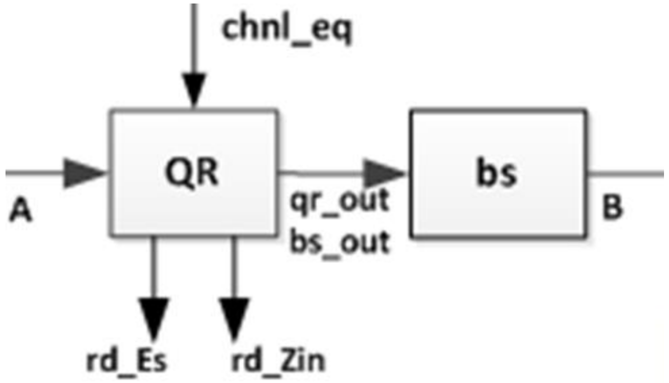
$$\mathbf{H} = \begin{bmatrix} h_{L-1} & \cdots & h_0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & h_{L-1} & \cdots & h_0 \end{bmatrix}$$

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

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

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

# Equalizer Implementation




Givens rotation for 4-by-4 matrix

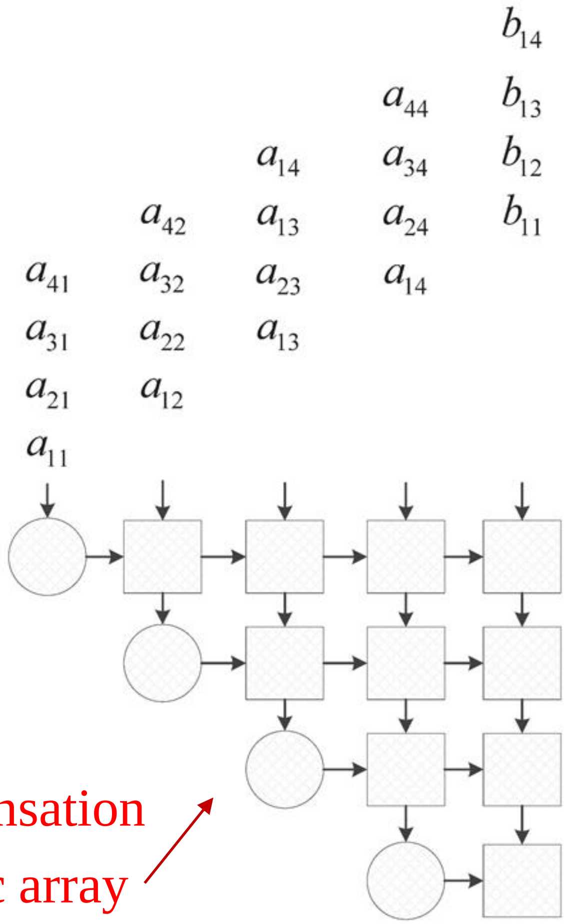
$$\mathbf{G}_1 = \begin{bmatrix} C_1 & S_1 & 0 & 0 \\ -S_1^h & C_1^h & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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

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

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

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

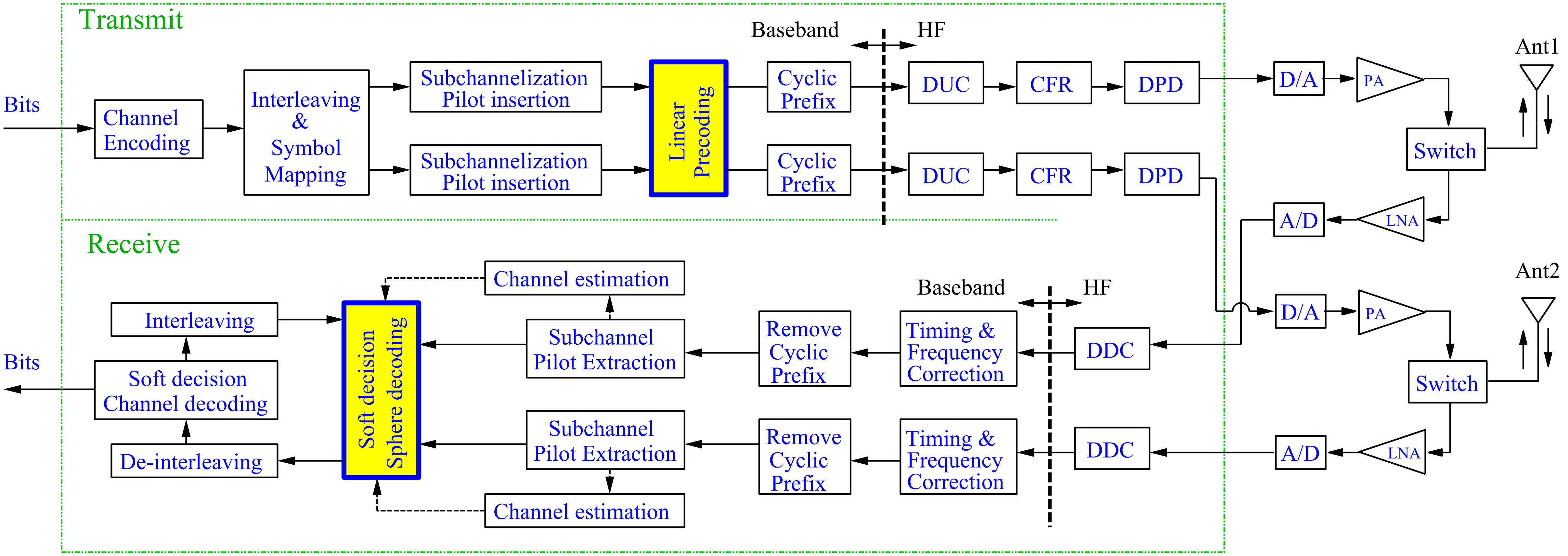


QR decompensation by 2D systolic array

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.

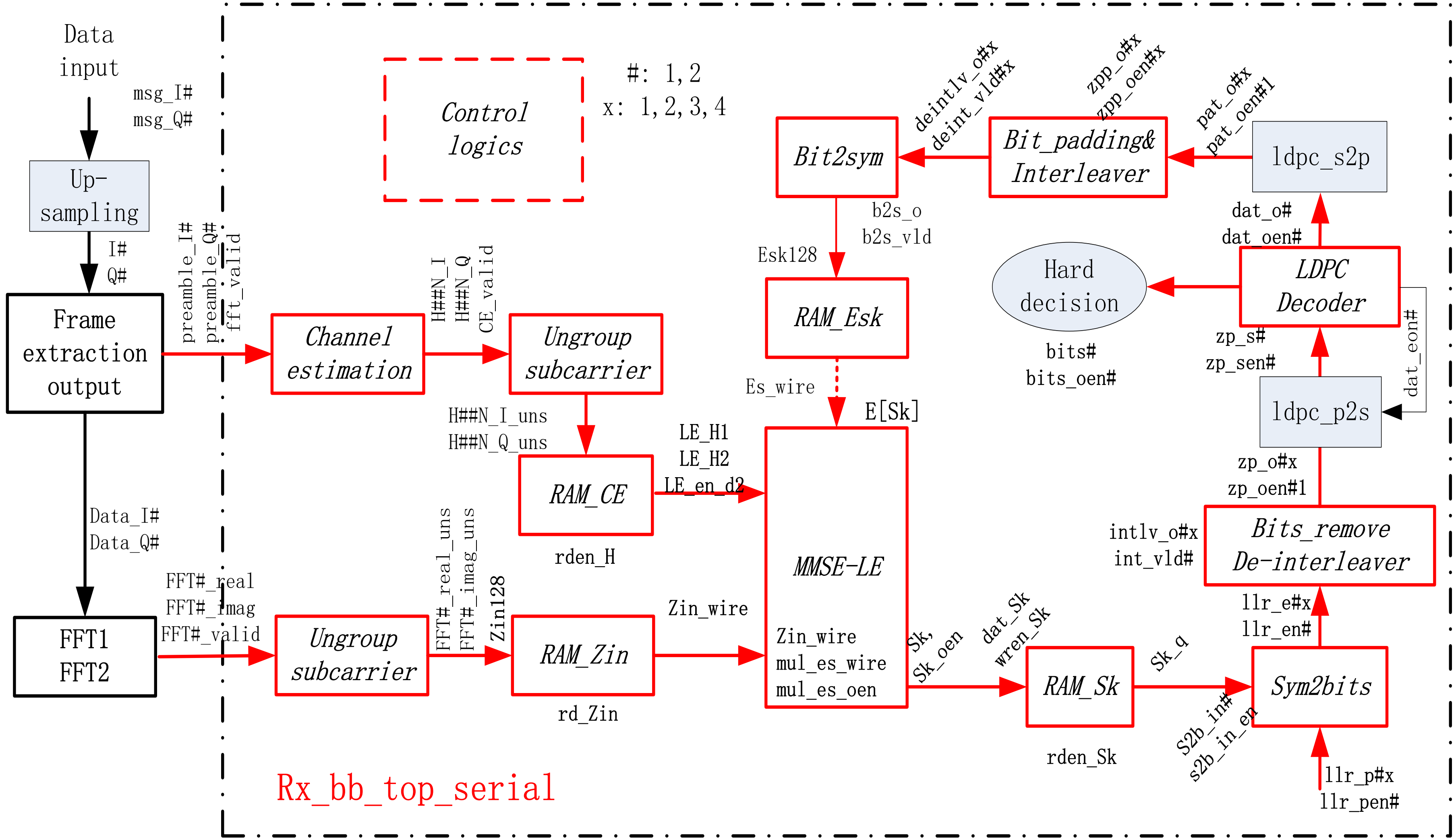
# FPGA Implementation of MIMO Transceiver

## ❑MIMO Transceiver with Turbo Equalization and Sphere Decoding.

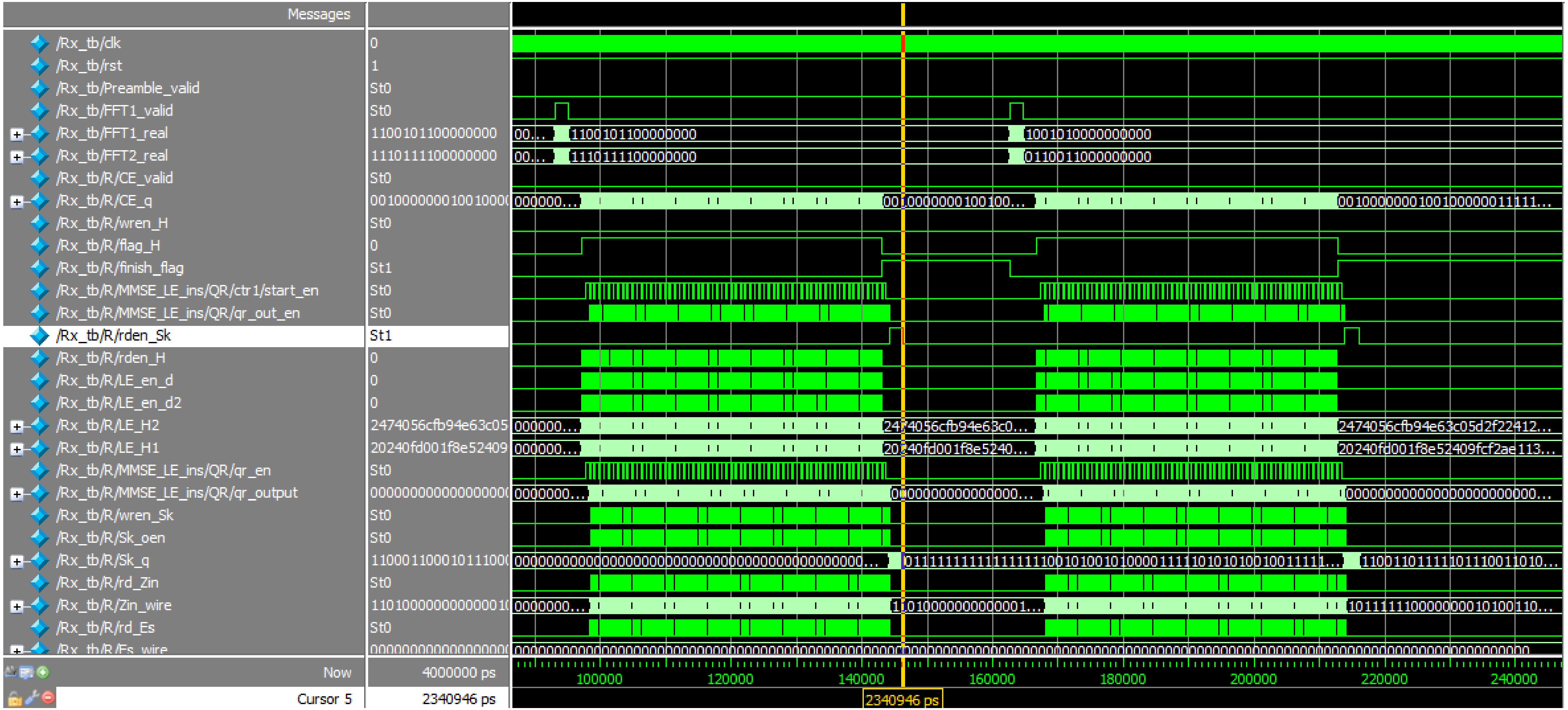



B. Han, Z. Yang, and **Y. R. Zheng**, “Efficient Implementation of an Iterative MIMO-OFDM Receiver Using MMSE Interference Cancelation,” IET Commun., vol. 8, No. 7, pp. 990 – 999, May. 2014.

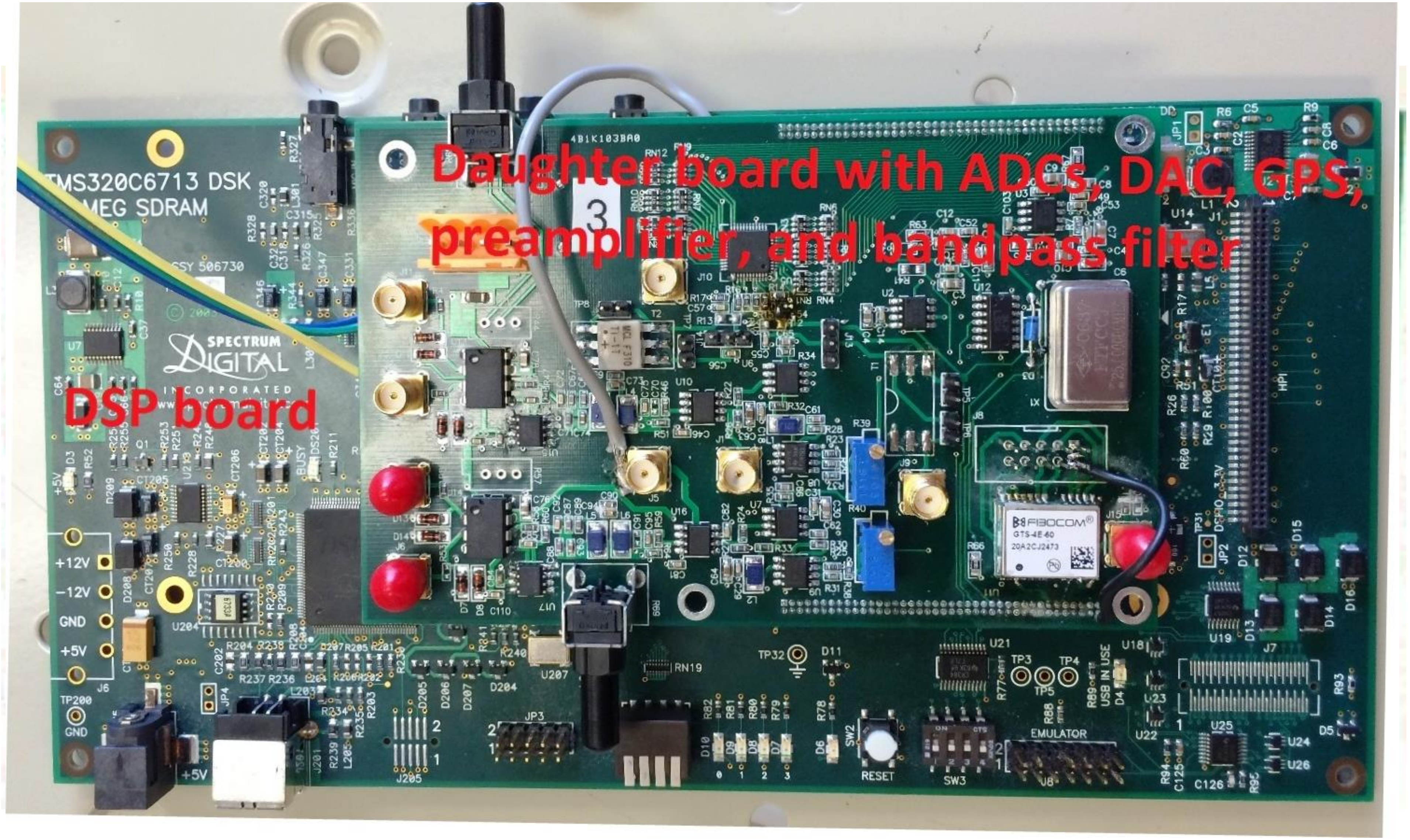
# Altera FPGA Stratix III & Stratix IV



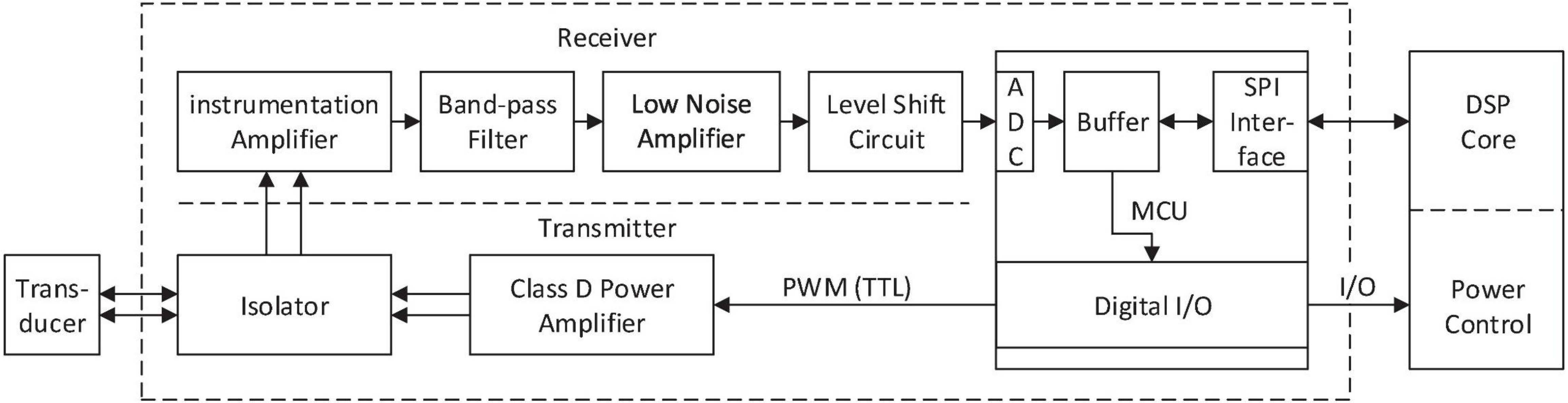

# Results of ModelSim Output



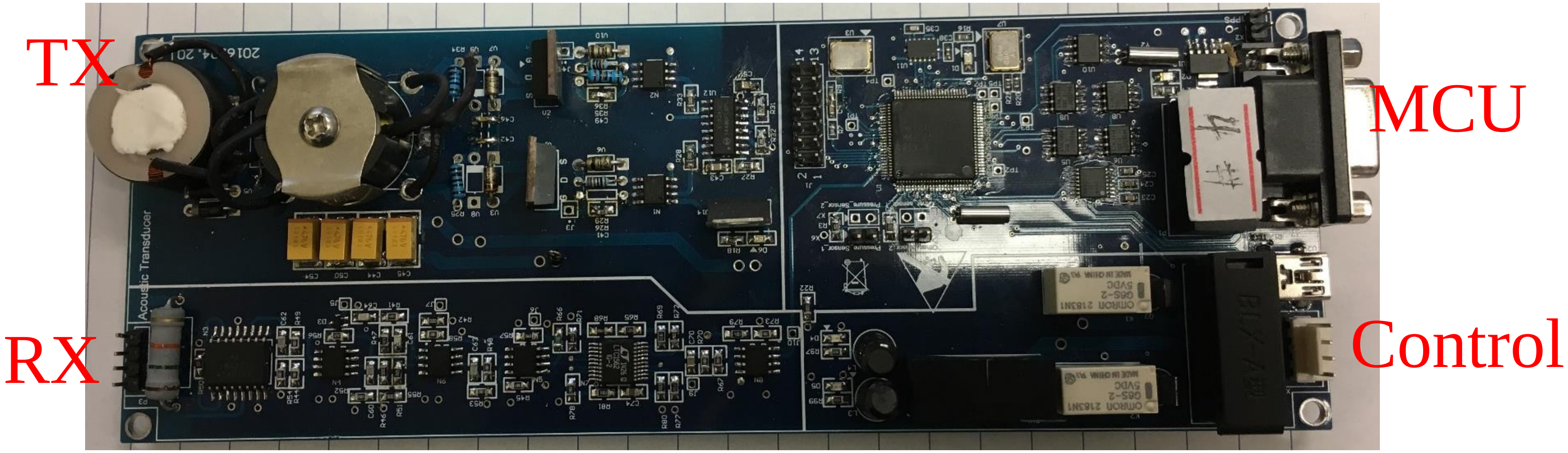
# TMS340C6713 DSK and Daughter Board



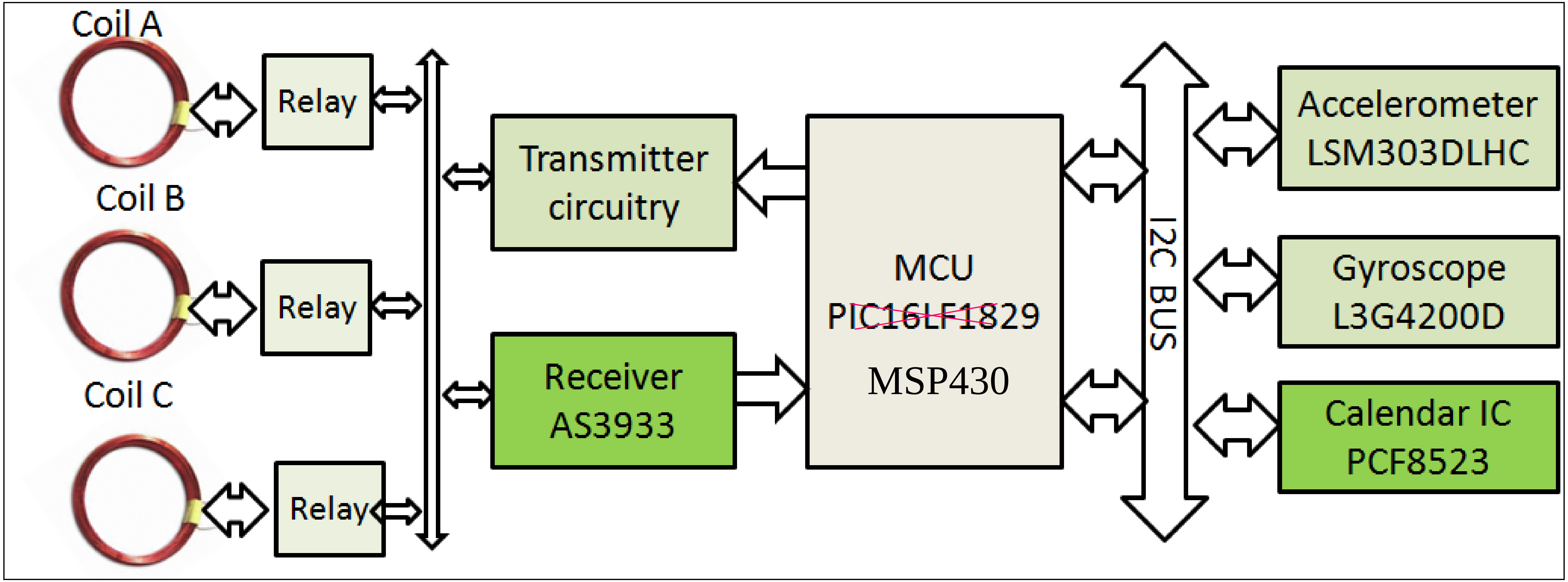
# Hardware Implementation w/ TI MCU





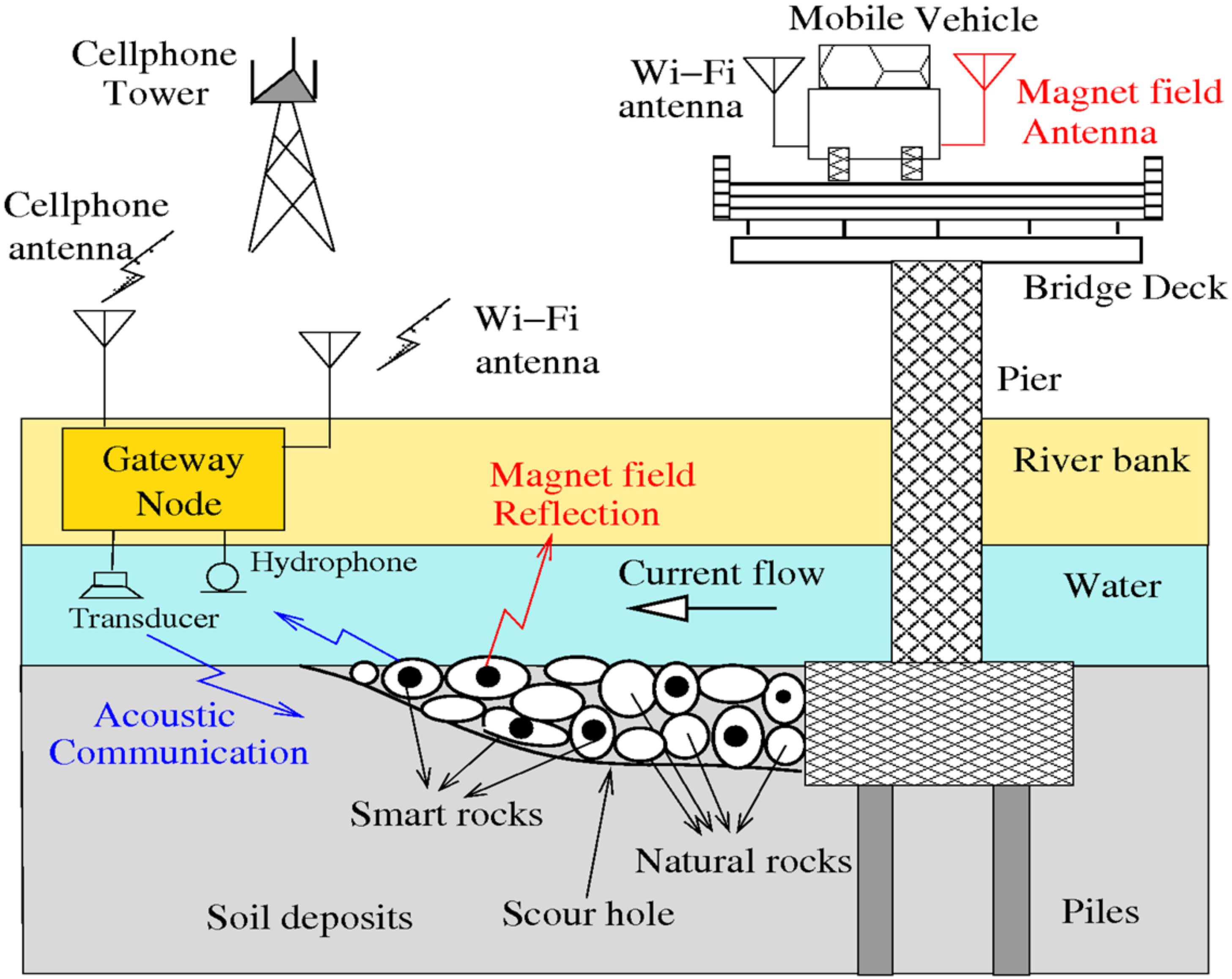


# MI Communication System



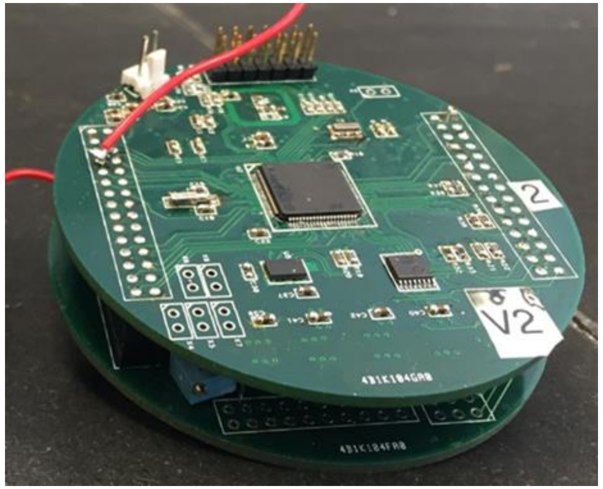

Version 3 MI system w/ 3-D antenna coils

# Underwater Internet of Things




Injectable Acoustic Fish Tracking Tag

# Bridge Scour Monitoring




Rock shells weigh 50 – 200 lb

# Bridge Tests

Gasconade River, July 2013

Rubidoux River, May 2018

# Conclusion and Future Work

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- Two of the three means in underwater wireless communication:
  - Ultrasound (acoustic) communications (Acomm);
  - Magneto-Inductive (MI) Communications.
- What are the most important factors: reliability, range, data rate, power consumption, small form factor, cost?
- Future work:
  - Hardware integration and field test;
  - Innovative network protocols and secure communication.