A MIMO Model for Copper Cable in EFM

John M. Cioffi, George Ginis, Jeannie Lee Fang

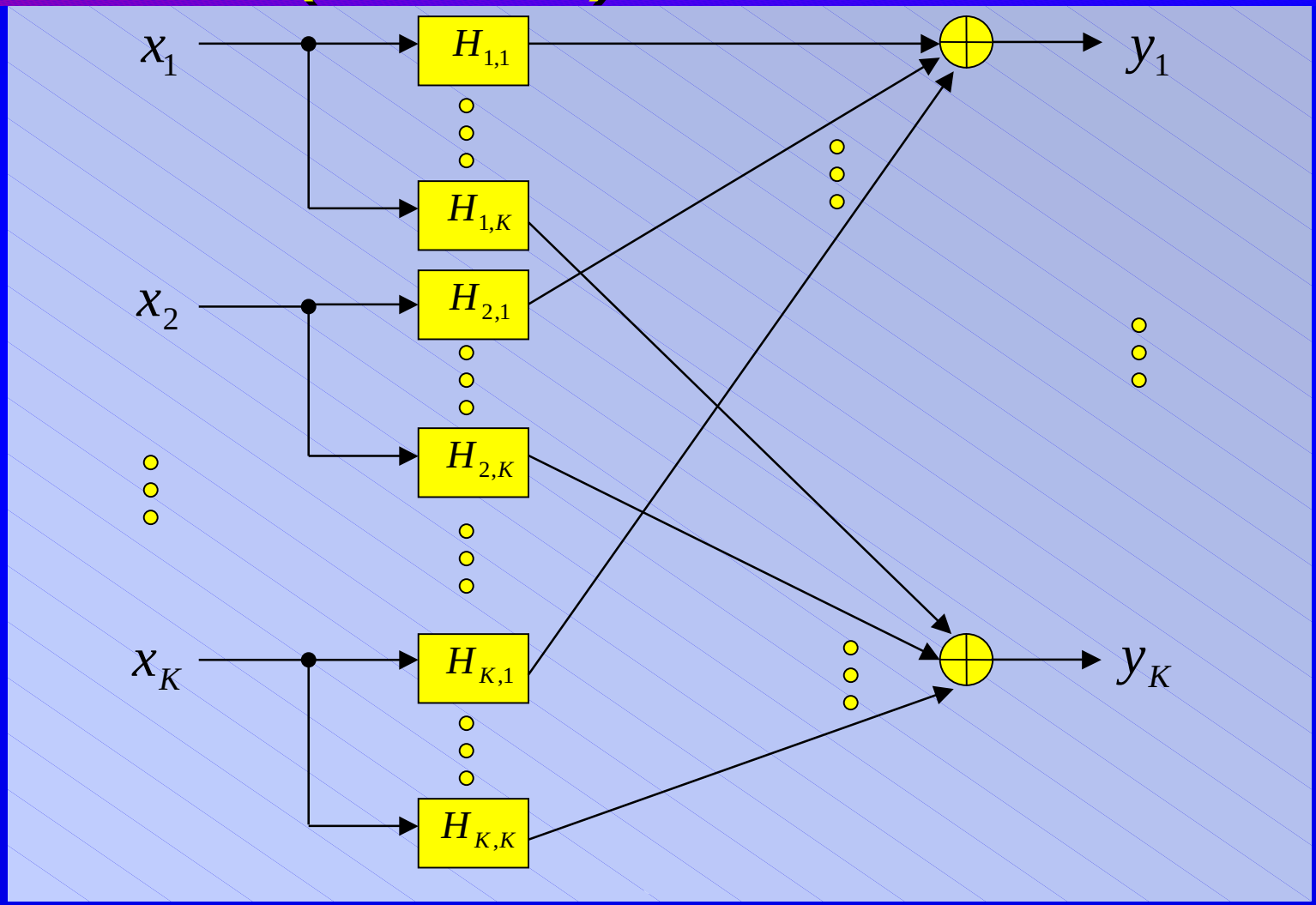
EE Dept, Stanford Univ.

Cioffi@stanford.edu

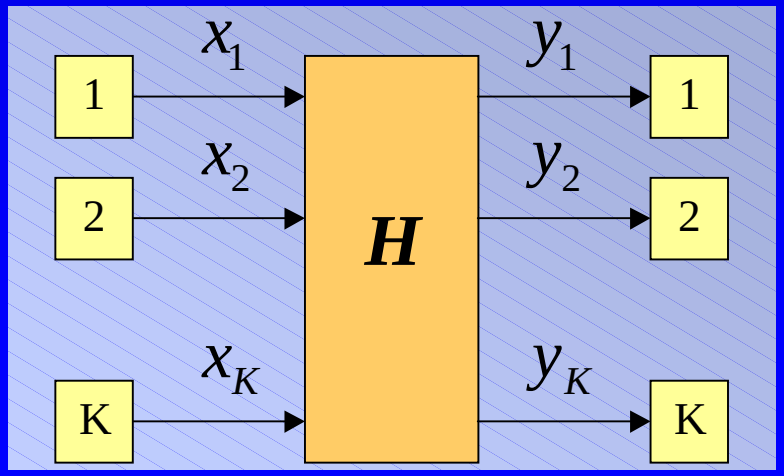
gginis@stanford.edu

jeanniel@stanford.edu

Multiple Input Multiple Output (MIMO) Channel



MIMO Channel



- Use vector notation to represent FEXT:

$$\mathbf{Y} = \mathbf{H} \cdot \mathbf{X}$$

- Channel matrix depends on frequency:

$$\mathbf{H} = \left[H_{mn}(f) \right]_{\substack{m=1,\ldots,K \\ n=1,\ldots,K}}$$

Motivation for MIMO model

- FEXT in EFM is a dominant noise source.
- FEXT mitigation schemes will gain importance.
- Appropriate MIMO model is needed to evaluate the performance and complexity of the various schemes.

Defining the Channel Matrix

- Assume all loops have equal length.
- Compute $H_{mm}(f) = H(f)$ from loop length and RLCG parameters.
- Start with FEXT power-sum model:

$$G(f) = k_{FEXT} \cdot f^2 \cdot d \cdot |H(f)|^2$$

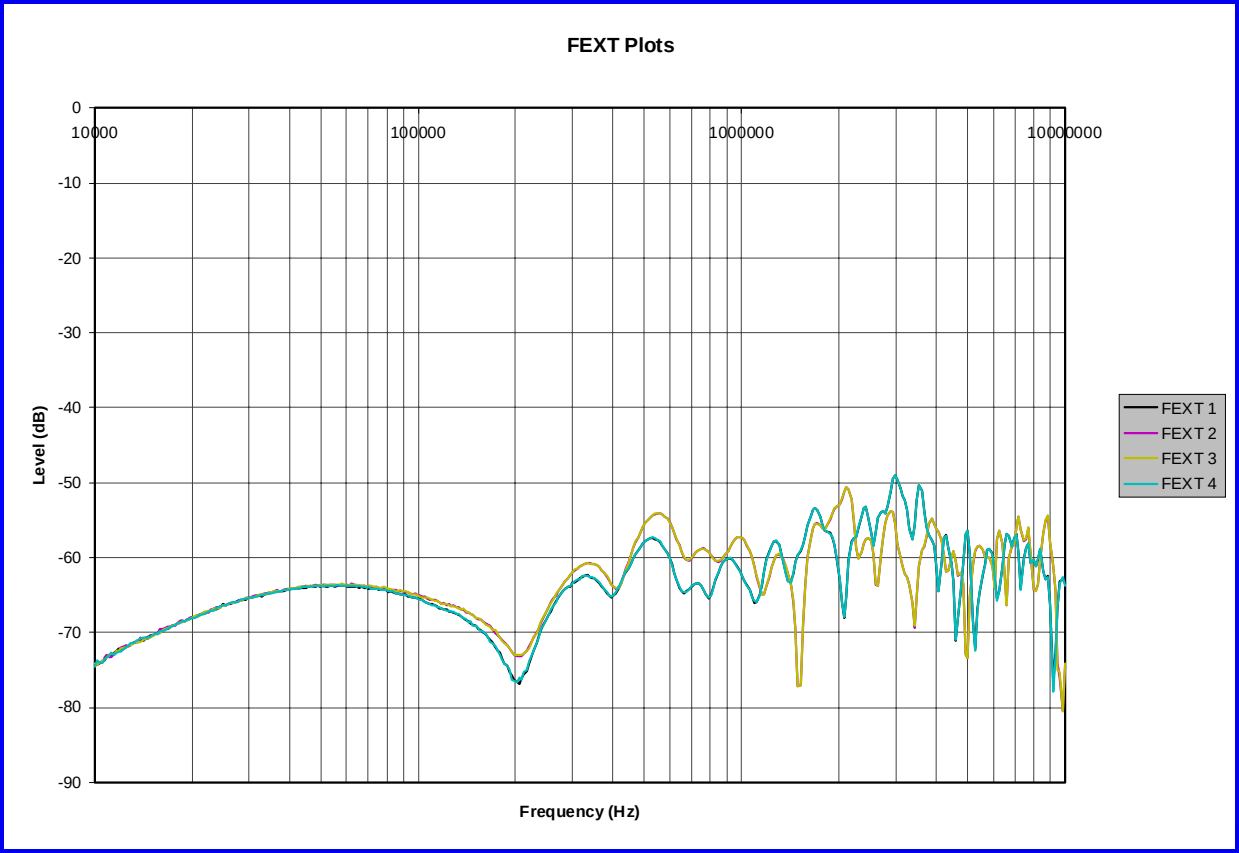
- Take square root to obtain off-diagonal transfer functions:

$$H_{mn}(f) = \sqrt{G(f)}$$

"Improving" the Off-diagonals

- Add phase term $\exp\left(j2\pi f\tau + j\phi_{mn}\right)$.
  - Delay τ makes response causal.
  - Phase ϕ_{mn} is picked randomly between 0 and 2π.
- Account for multiple lines by multiplying with: $N_{lines} = \sqrt{(K-1)^{0.6}/(K-1)} = (K-1)^{-0.2}$

Real FEXT Measurements



- 500 meter FEXT (courtesy of John Cook, BT)

- Model MUST account for frequency variation.

Proposed Model

$$H_{mn}(f) = \begin{cases} H(f) & m = n \\ k_{cross}\, f\, |H(f)| e^{j(2\pi f\tau + \phi_{mn})} \left[1 + 0.3\cos\left(\frac{2\pi f d}{c_{line}}\right) - 0.3\cos\left(\frac{4\pi f d}{c_{line}}\right) \right] & m \neq n \end{cases}$$

- $k_{cross} = \sqrt{k_{FEXT} \cdot d \cdot N_{lines}}$ is a constant.
- Cosine terms provide a close approximation to the location of the dips and peaks in frequency seen on the previous slide.

Model Parameters

- c_{line} is speed of light on medium.
- CAT-5 crosstalk is 10dB weaker.
- Telco-quad crosstalk is 10dB stronger.

	Category 5 Quad	Category 3	Telco Quads
$\sqrt{k_{FEXT}}$	4.8×10^{-12}	4.8×10^{-11}	4.8×10^{-10}
N_{lines}	1	$49^{-0.2} = 0.459$	1

Conclusion

- Need MIMO model for copper cable.
- Proposed channel matrix model taking into account:
  - FEXT power-sum model.
  - Random phase for crosstalk.
  - Effect of multiple lines.
  - Additional frequency variation.