Space-Time-Frequency Methods for Interference-Limited Communication Systems

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PhD Defense

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WNCG
Wireless Networking & Communications Group

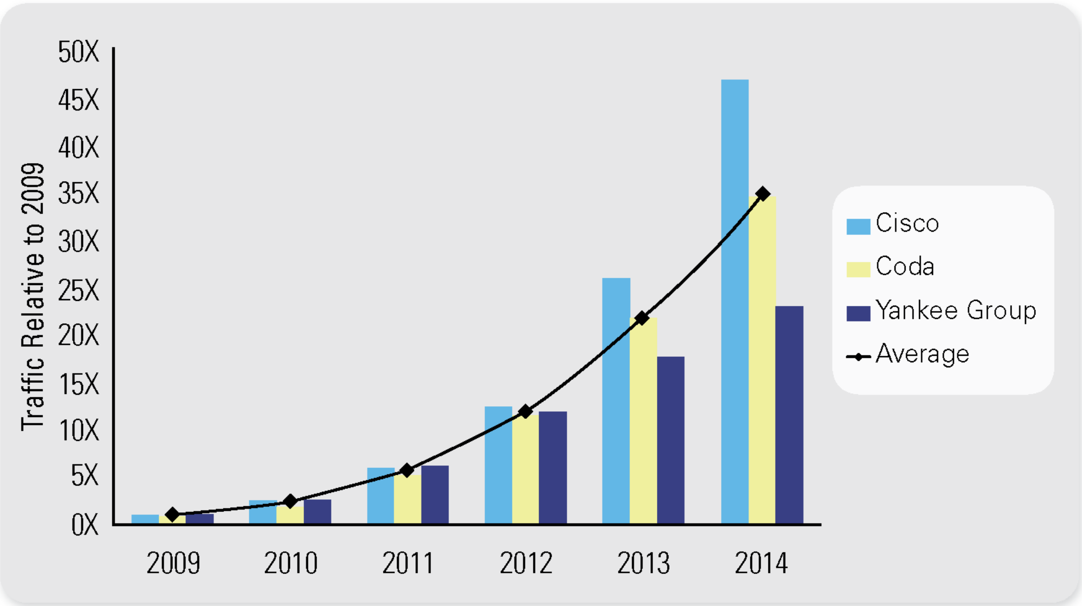
Wireless Research – Some Perspective

Pope Election 2005

Pope Election 2013

What a difference in just 8 years!

Relentless Demand for More Data

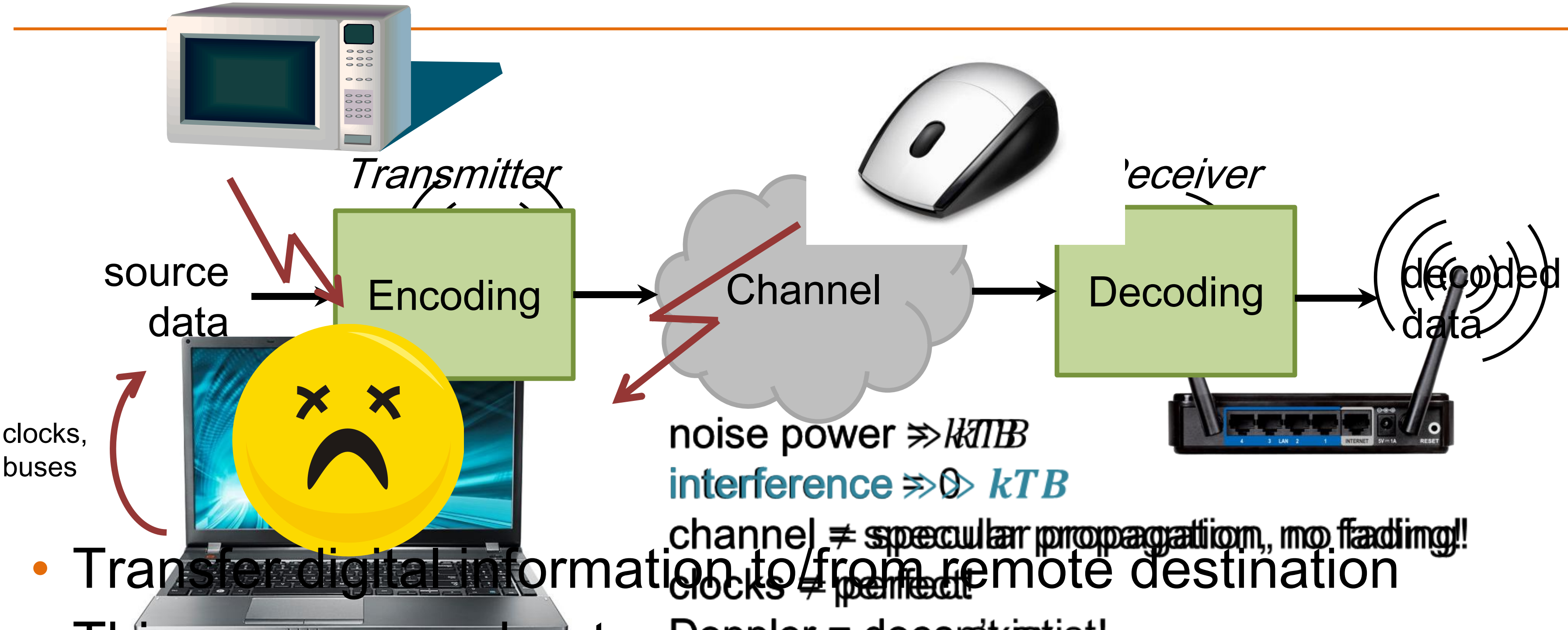

Industry Forecasts of Mobile Data Traffic

From Mobile Broadband: The Benefits of Additional Spectrum (FCC Report 10/2010)

Digital Communications

What We Wish Channels Were Like…

Realistic



noise power = kTB

noise power ≫ kTB

interference = 0

interference ≫ kTB

channel = specular propagation, no fading!

channel ≠ specular propagation, no fading!

clocks = perfect!

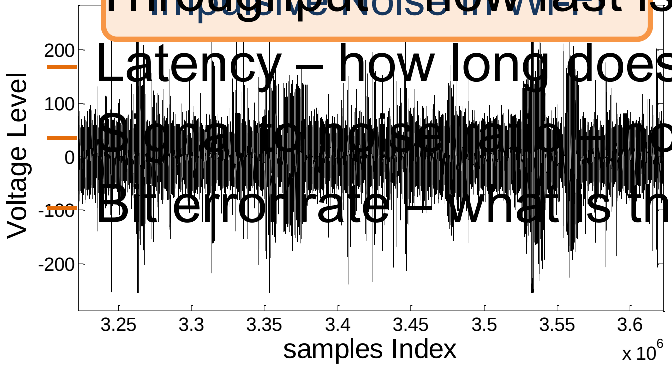
clocks ≠ perfect

Doppler = doesn't exist!

Doppler = exists!

- Transfer digital information to/from remote destination
- Things we care about
  - Throughput – how fast is source information moving over the link?
  - Latency – how long does it take for information to get there?
  - Signal to noise ratio – how noisy is the channel?
  - Bit error rate – what is the probability that bits are decoded incorrectly?

Impulsive Noise in WiFi



Interference-Limited Communications

Underwater Acoustic

Powerline Communications

Multi-Antenna Cellular

- Thesis statement:

  Multi-dimensional signal processing methods can be applied to dramatically enhance communication performance without sacrificing real-time requirements.

Contributions

Space-Time-Frequency Methods for Interference-Limited Communication Systems

Space-Time for Underwater Acoustic

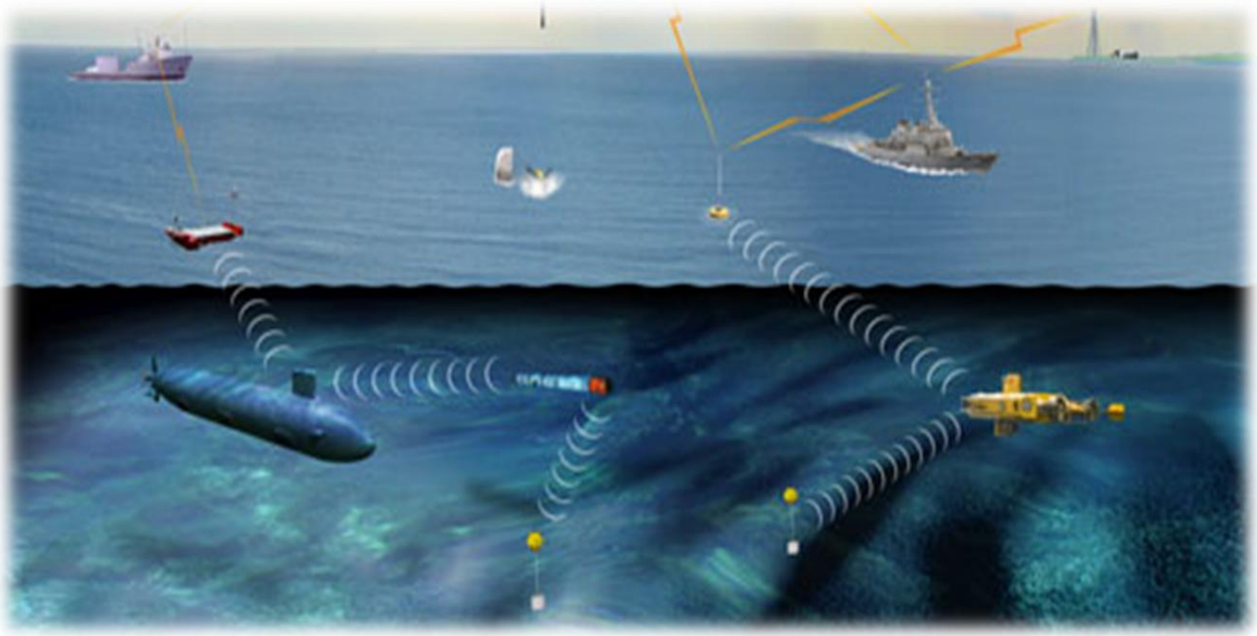
- Wideband, space-time interference suppression
- Sum-efficiencies 10x above prior state-of-the-art

Time-Frequency for Powerline

- Cyclic modulation and impulsive noise mitigation
- Up to 28 dB operating point improvements

Space-Time-Frequency for Cellular

- Real-time framework for up to 128 antenna MIMO
- Used in world's first 100-antenna testbed



First Contribution

Space-Time Methods for Underwater Acoustic Communications

Figure taken from: http://www.l-3mps.com/maripro/throughwateracousticcomm.aspx

Underwater Acoustic Physics

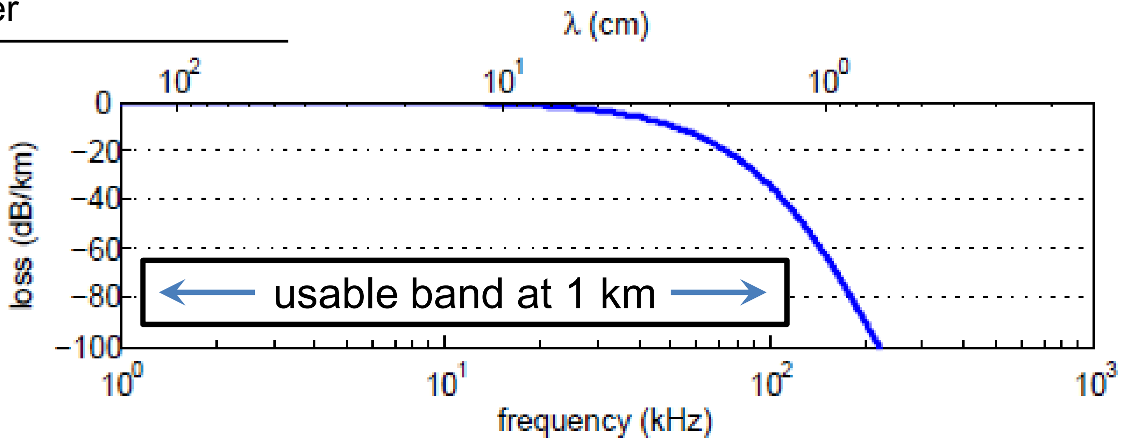
- Data is modulated on longitudinal acoustic pressure waves
- Different physics from radio frequency (RF) propagation
  - 200,000x slower than RF in free space
  - Highly complex propagation, particularly in shallow water environments

Typical Medium Range System

range (km)	0.02 – 10
bandwidth (kHz)	1 – 100
center frequency (kHz)	5 – 100
ratio of attainable speed to propagation speed for typical user	0.00 – 0.01

For comparison, SR-71 jet at Mach 3.4 achieves only 0.0000034 c_{RF}

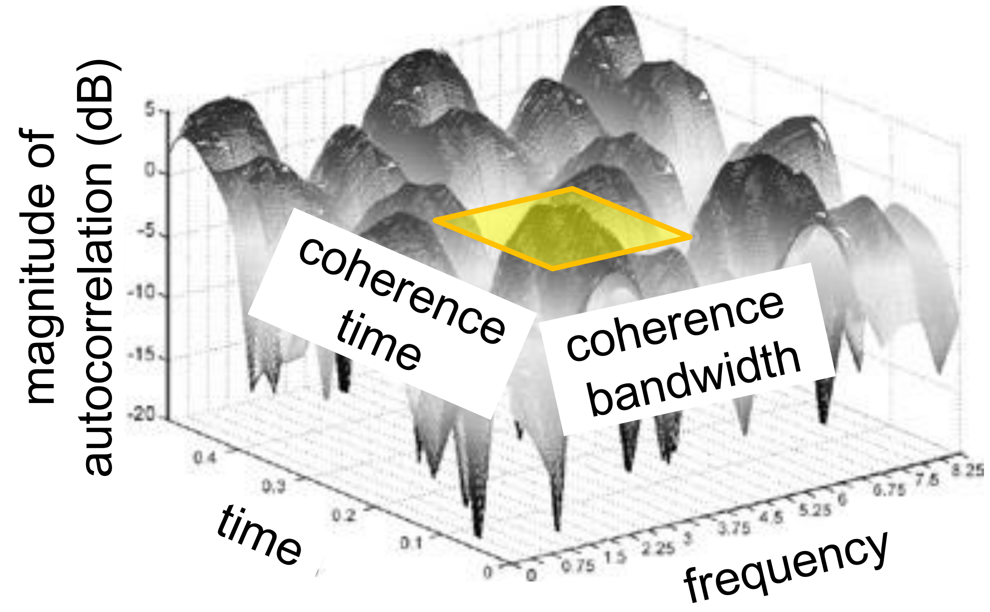
Absorptive mechanisms include viscosity, strain relaxation, heat conduction



Time-Frequency Coherence

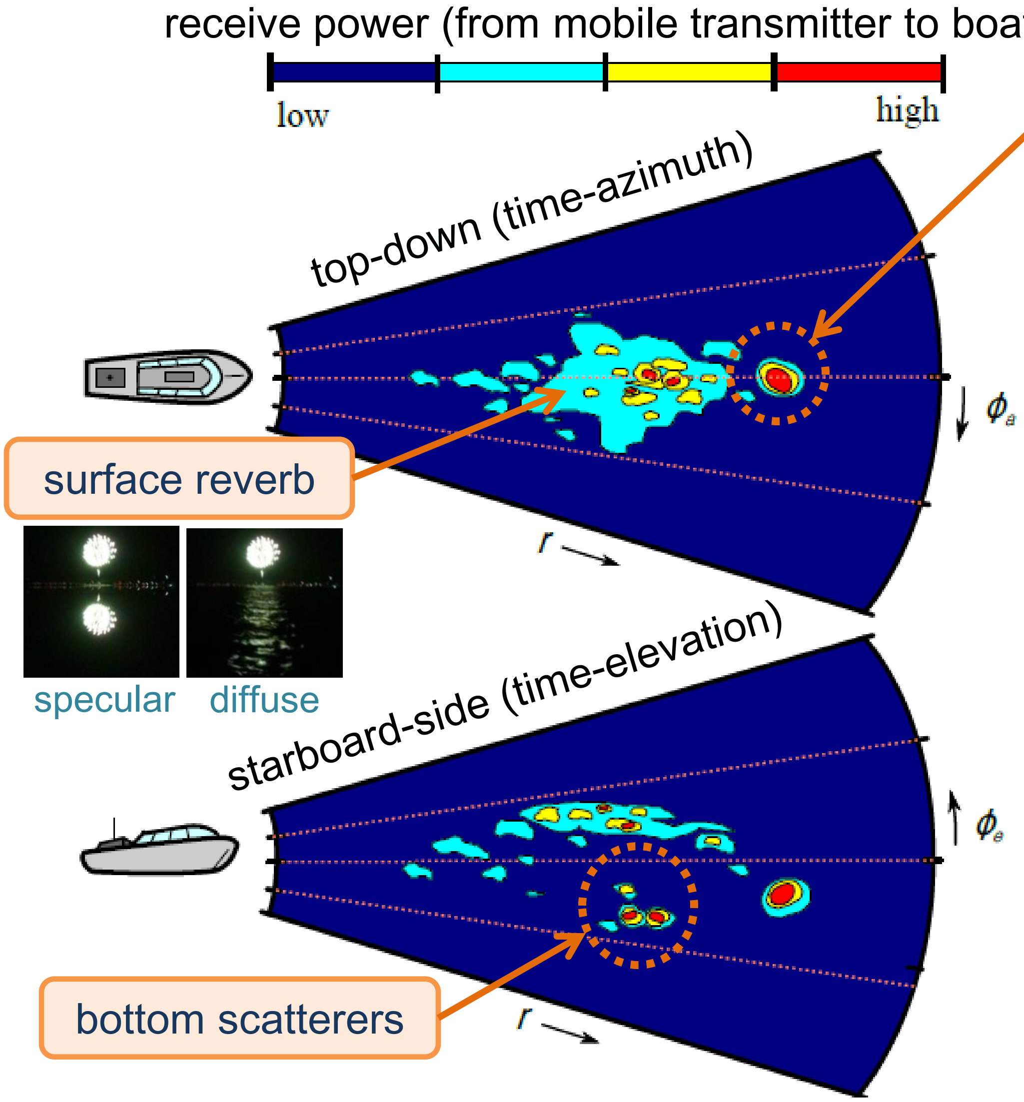
- Wideband methods must be used due to large relative bandwidths
- Slow sound speed → doubly-selective
- Adaptive equalization supports fixed time/ bandwidth area[Bea04]

http://ltesignaling.blogspot.com/2011/12/radio-interface-basics.html



	Acoustic	RF Cellular
RMS delay spread	3.3 ms	2 μs
coherence time	1 ms	1.2 ms
Doppler dilation factor	0.01	3.24×10^{-7}
relative bandwidth	1.0 for f_c = 30 kHz, 30 kHz bandwidth	0.0072 for f_c = 2.6 GHz, 18 MHz bandwidth

Space-Time-Frequency Coherence

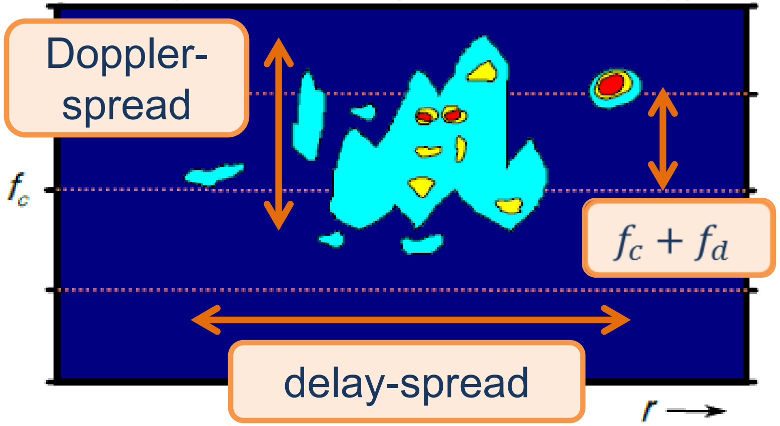


http://www.optimismnow.com/optimism-blog/tag/happiness

line-of-sight component

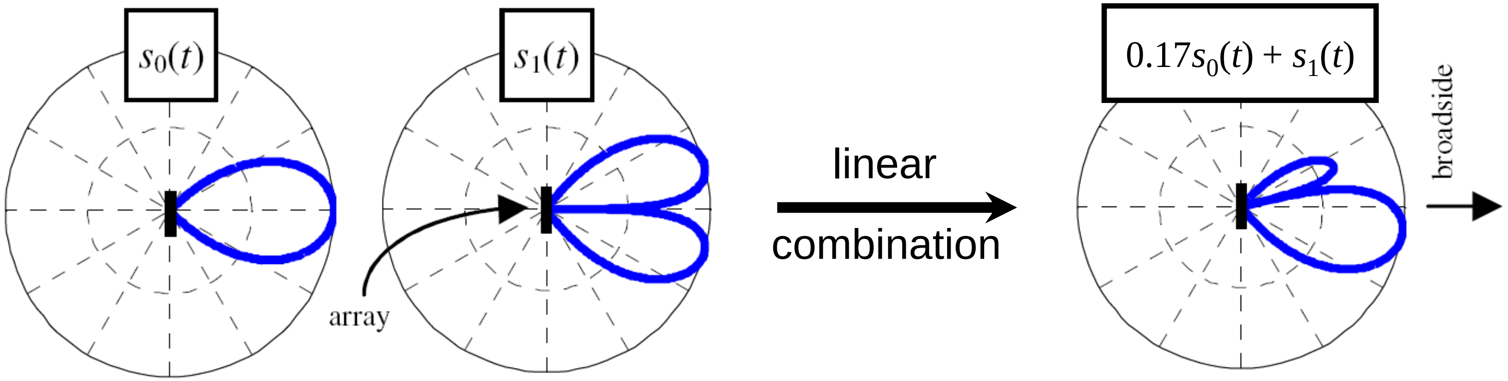
- 4-D coherence properties of shallow water channel
- Based on high resolution imaging SONAR data
- Can be used to derive 4-D marginal of signal

range-Doppler (time-frequency)



Adaptive Space-Time Interference Suppression

- Space-time monopulse prefilter applied to array outputs[Hen85]
- Beam pairs with frequency-invariant properties are produced



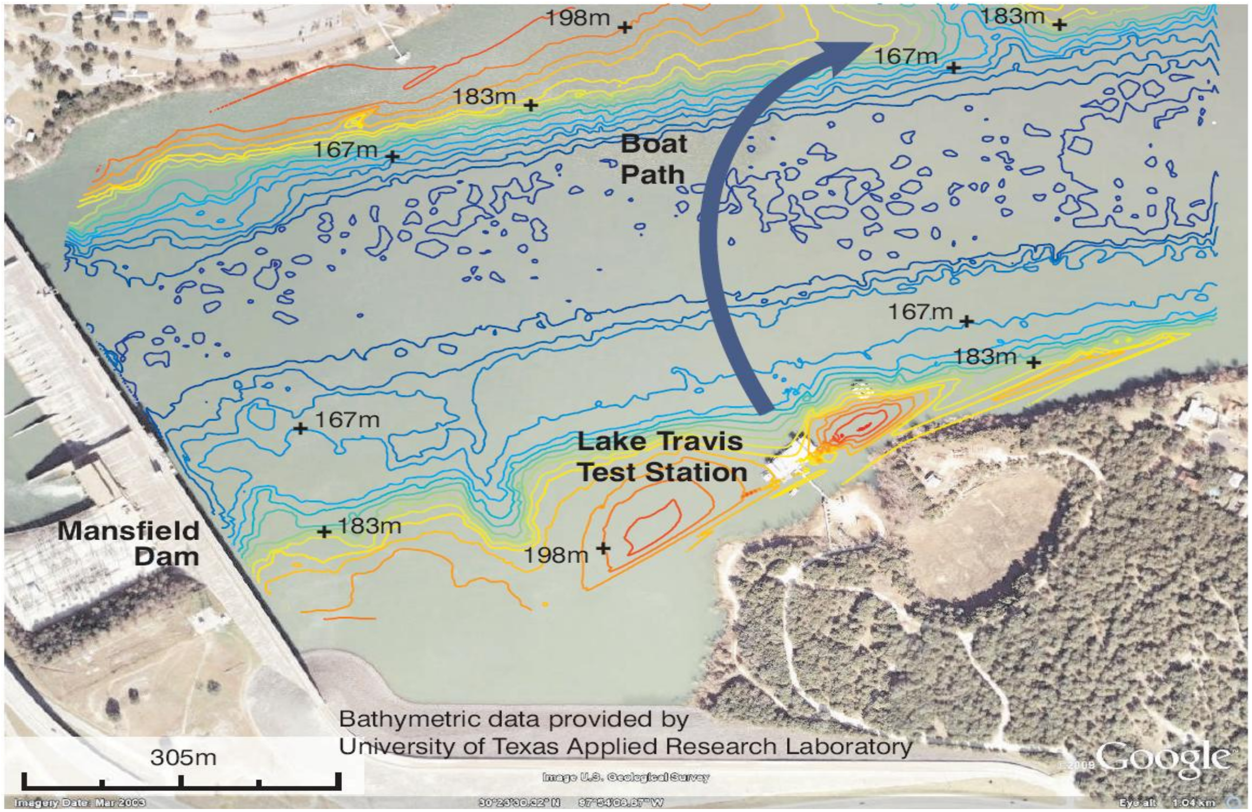
- Broadband beampattern has no nulls, yet linear combination can be used to create beam $x(t)$ with deep null at angle θ_n

$$x(t) = s_1(t) - (\sin\theta_n - \sin\theta_s)s_0(t)$$

- Reduction in channel count has two benefits
  1. Computational complexity is substantially reduced
  2. Time-frequency coherence of adaptive equalizer is increased

Shallow Water Acoustic Data Collection

- Mobile research vessel transmits back to stationary array at test station
- ~5 TB of acoustic data collected and analyzed over 2 yr project
  - Methods developed for Doppler tracking[Per10], monopulse[Nie10a], and equalizer design[Nie10b]



Bathymetric data provided by University of Texas Applied Research Laboratory

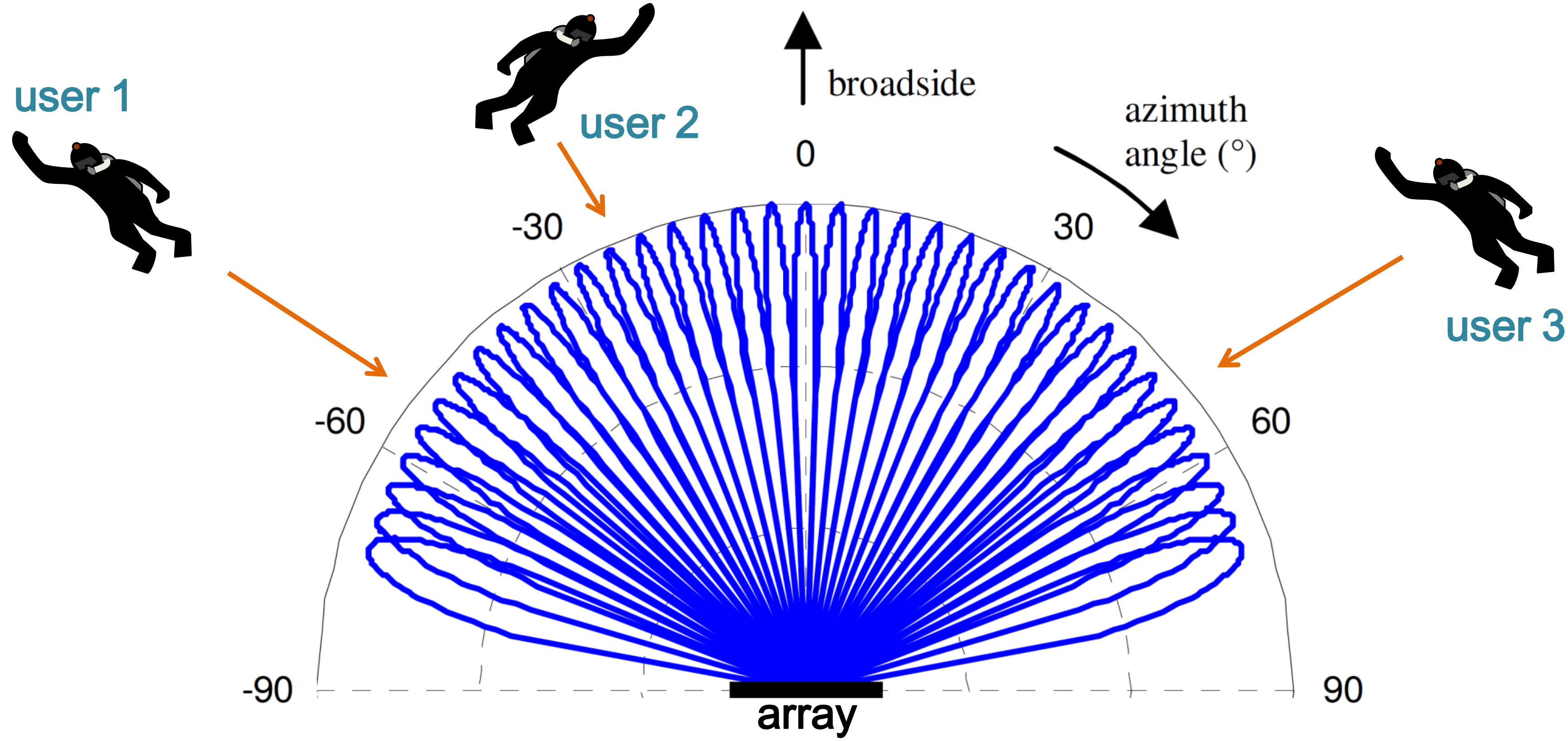
Overhead view of Lake Travis Test Station with overlaid bathymetric map

Prior Empirical Results

- Close fit to *empirical range-rate bound* of 40 kbps/km[Kil00]
  - Target bit-error-rates of 10^{-1} and 10^{-2}

Method	Number of Elements/ Array Geometry	Center Frequency (kHz)	Range (km)	Rate (kbps)	Bound (kbps)	Sum-Rate Efficiency (bps/Hz)
Multi-Channel Adaptive Equalization[Fre08]	8 vertical or horizontal line, multi-user	23	0.5-2	2.8	20	0.56
Channel Eigen Decomposition [Bea04]	64 cross-beam	24	3.2	16	12.5	1.0
Spatial Filter then Equalizing [Yan07]	32 vertical line	1.2	10	0.4	4	1.0
OFDM[Sto08]	8 vertical	25	1	24	40	2.0
Single-Carrier MIMO[Tao10]	8 vertical receive, 2 vertical transmit	17	1-3	32	13.3	2.3

Spatial-Division Multiple Access (SDMA) + Monopulse



- Multiple azimuthal users supported via orthogonal beam set
- Monopulse dynamically suppresses up to 14 dB interference
- Achieved sum rate of 28 bps/Hz serving 40° sector

New Empirical Results

- Achieved sum-spectral efficiencies **10x** prior state-of-the-art
  - Target bit-error-rates of 10^{-1} and 10^{-2}

Method	Number of Elements/ Array Geometry	Center Frequency (kHz)	Range (km)	Rate (kbps)	Bound (kbps)	Sum-Rate Efficiency (bps/Hz)
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Single-Carrier MIMO[Tao10]	8 vertical receive, 2 vertical transmit	17	1-3	32	13.3	2.3
Monopulse + SDMA[Nie11]	2-D w/ hundreds, 7 simultaneous users	--	--	1400	--	28

Contribution 1 Summary

Highlights
Develop methods for enhanced Doppler tracking and equalization
Develop space-time reverberation (interference) reduction method
Demonstrate sum spectral efficiencies 10x above prior state-of-the-art

Relevant work

[Nie11] – **K. F. Nieman**, K. A. Perrine, T. L. Henderson, K. H. Lent, and T. J. Brudner, "Sonar array-based acoustic communication receivers with wideband monopulse processing," *USN Journal of Underwater Acoustics*, 61(2), 2011.

[Nie10a] – **K.F. Nieman**, K.A. Perrine, T.L. Henderson, K.H. Lent, T.J. Brudner, and B.L. Evans, Wideband monopulse spatial filtering for large receiver arrays for reverberant underwater communication channels. *Proc. IEEE OCEANS*, 2010.

[Per10] – K.A. Perrine, **K.F. Nieman**, T.L. Henderson, K.H. Lent, T.J. Brudner, and B.L. Evans. Doppler estimation and correction for shallow underwater acoustic communications. *Proc. IEEE Asilomar Conference on Signals, Systems, and Computers*, 2010.

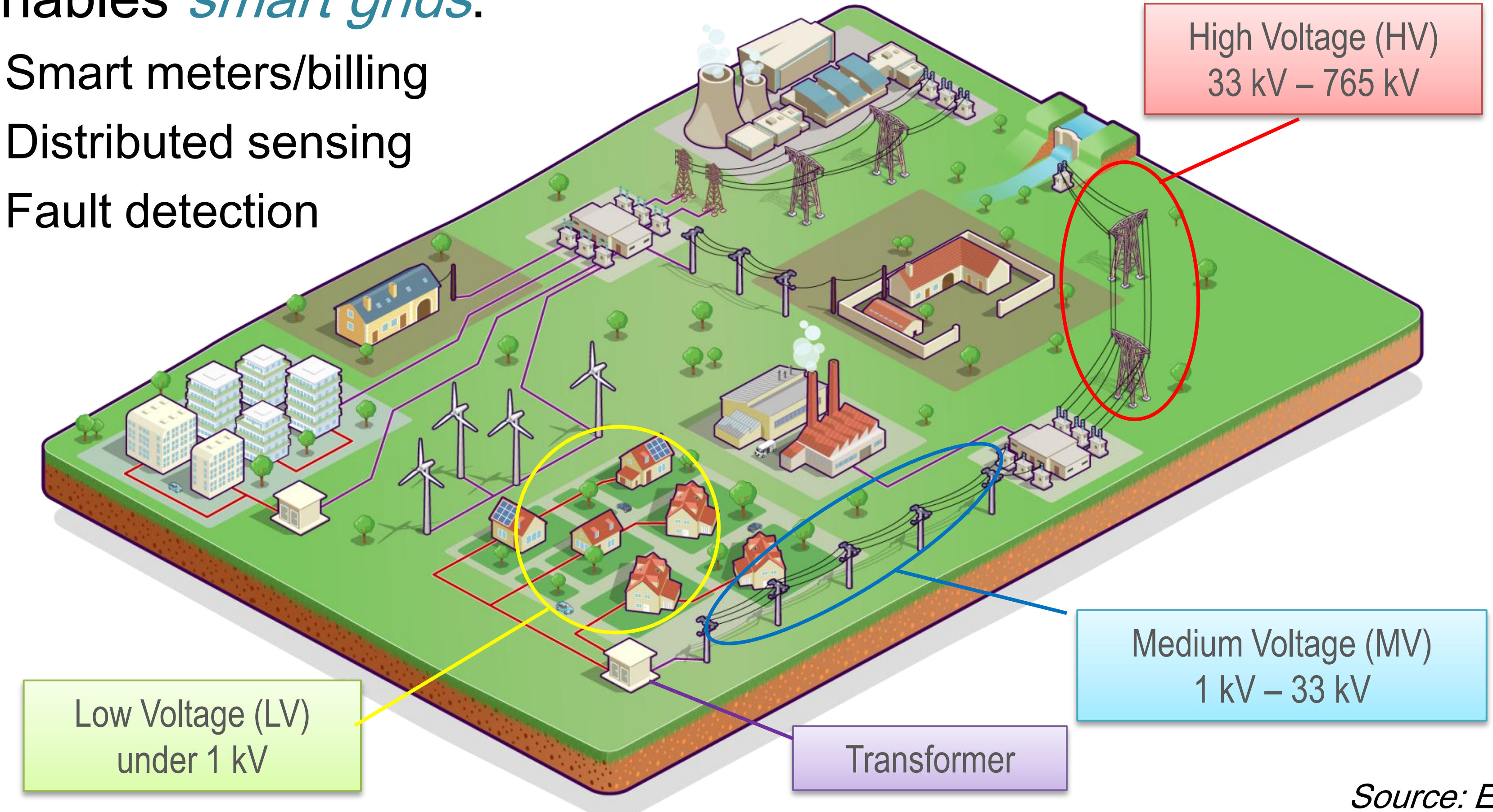
[Nie10b] – **K.F. Nieman**, K.A. Perrine, K.H. Lent, T.L. Henderson, T.J. Brudner, and B.L. Evans. Multi-stage and sparse equalizer design for communication systems in reverberant underwater channels. *Proc. IEEE Workshop on Signal Processing Systems*, 2010.

Second Contribution

Time-Frequency Methods for OFDM Powerline Communications

Powerline Communications (PLC)

- Power grid originally designed for power distribution
- Form networks by coupling in communication signals
- Enables *smart grids*:
  - Smart meters/billing
  - Distributed sensing
  - Fault detection

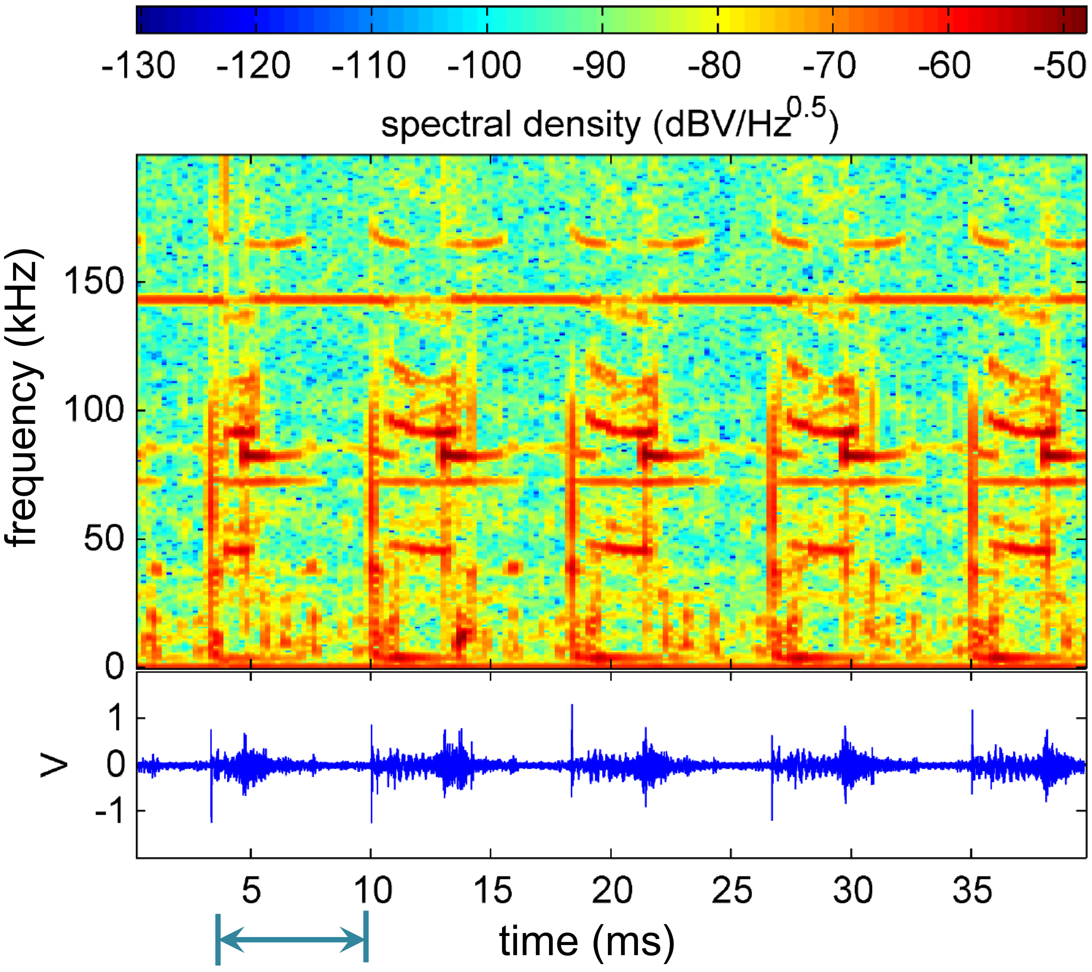


Source: ERDF

PLC Noise in the 0-200 kHz Band

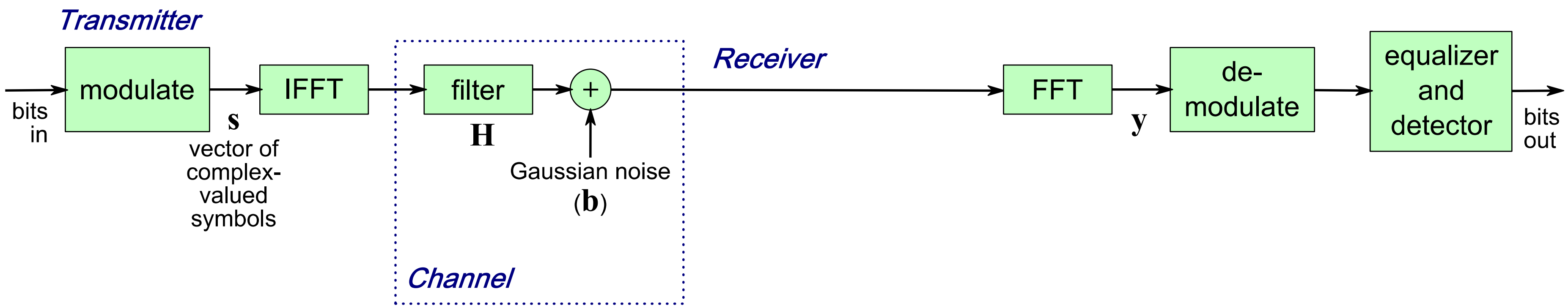
- Primary components
  1. Cyclostationary
  2. Asynchronous impulsive
- Sources include
  - Light dimmers/ballasts
  - Switching converters
  - Induction motors
  - Rectifiers
- Limited noise mitigation in PLC standards:
  - G3-PLC[Max11]
  - PRIME[Pri13]
  - IEEE P1901.2[Iee13]
  - ITU G.9901-9904[Itu13]

low-voltage noise measured in Austin, TX [Nie13a]



$T_{noise} = \frac{T_{AC}}{2}$ = 8.33 ms (120 Hz) in USA

Conventional OFDM PLC System

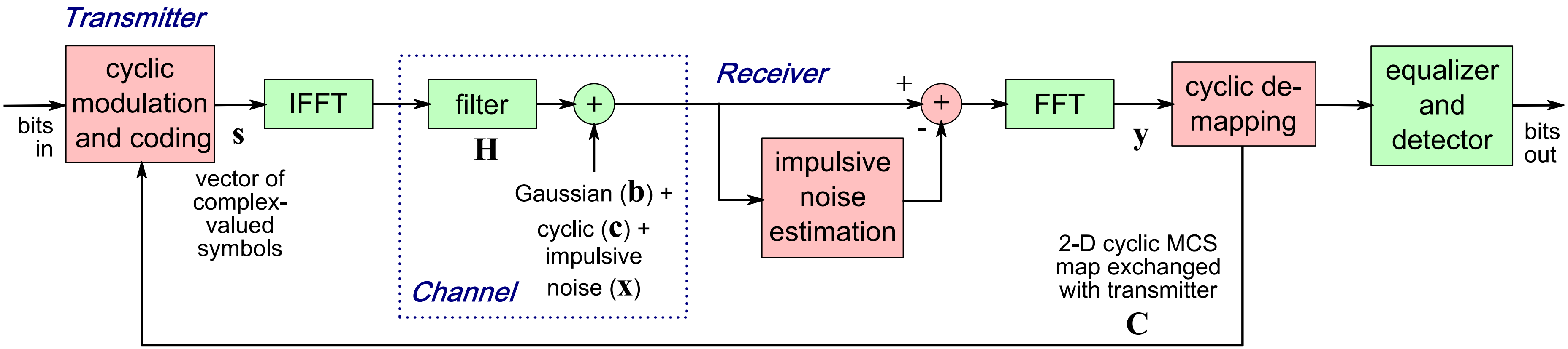


$$\mathbf{y} = \mathbf{F}\mathbf{H}\mathbf{F}^H\mathbf{s} + \mathbf{F}\mathbf{n}, \quad \text{where } \mathbf{n} = \mathbf{b}$$

additive white Gaussian noise $\mathbf{b} \sim \mathcal{N}(0, \gamma_B)$

- Built upon orthogonal frequency-division multiplexing (OFDM)
  - Splits communication signal into orthogonal sub-bands
- Standards address cyclic and impulsive noise through
  - Robust modulation, interleaving, and error-correcting codes
  - Designed to uniformly distribute signal – *not rate optimal*

Proposed OFDM PLC System

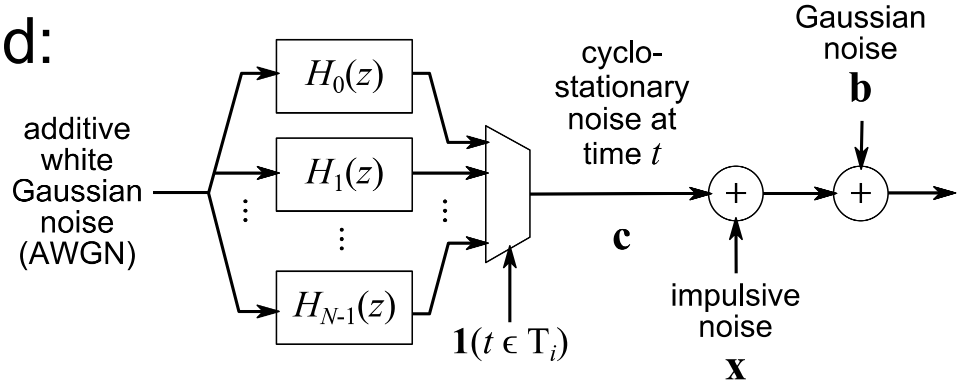


$$\mathbf{y} = \mathbf{F}\mathbf{H}\mathbf{F}^H\mathbf{s} + \mathbf{F}\mathbf{n}, \qquad \text{where } \mathbf{n} = \mathbf{c} + \underbrace{\mathbf{b} + \mathbf{x}}$$

cyclostationary, noise w/ power spectral density $S_{cc,i}(z) = |H_i(z)|^2$ during cycle subinterval T_i

asynchronous Gaussian mixture noise
$\mathbf{b} + \mathbf{x} \sim \mathcal{GM}(\pi, \gamma_B, \gamma_X)$
$= \pi\mathcal{N}(0, \gamma_B + \gamma_X) + (1-\pi)\mathcal{N}(0, \gamma_B)$

- Using new noise model, add:
  1. Impulsive noise mitigation
  2. Cyclic adaptive modulation and coding



Impulsive Noise Mitigation Techniques

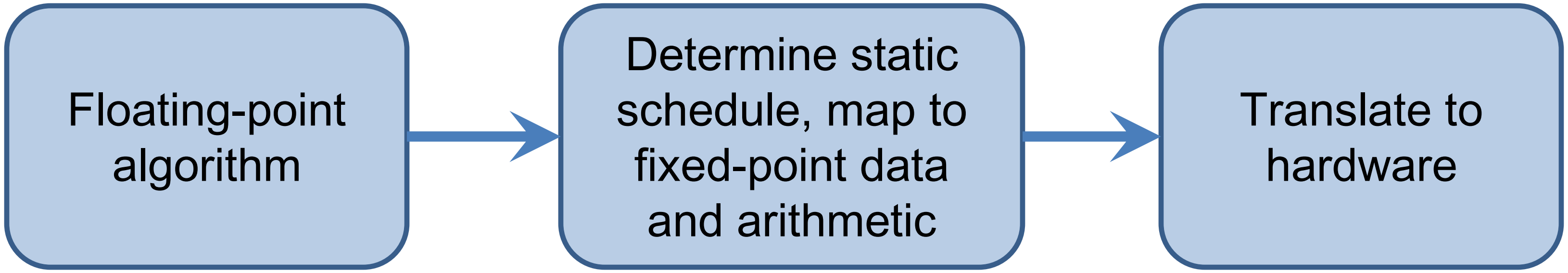
- Compressive sensing approach used for low impulse power
- AMP provides best performance vs. complexity tradeoff

compressive sensing

Method	Impulse Power		Non-Parametric?	Computational Complexity
	Low	High		
Nulling/ Clipping[Tse12]		✓		Low
Iterative Decoding for OFDM[Har00]	✓	✓		High
Thresholded Least Squares/MMSE[Cai08]		✓		Med
Sparse Bayesian Learning[Lin13]	✓	✓	✓	High (matrix inversion)
l_1-norm minimization[Cai08]	✓	✓	✓	High
Approximate Message Passing (AMP)[Nas13, Nie13]	✓	✓		Med

Implementation Process

- Implemented using field programmable gate arrays (FPGAs)[Nie13b]

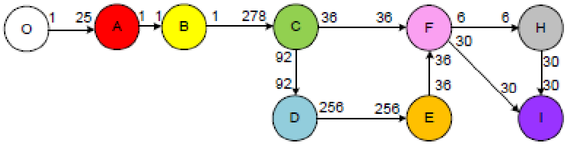


Floating-point algorithm

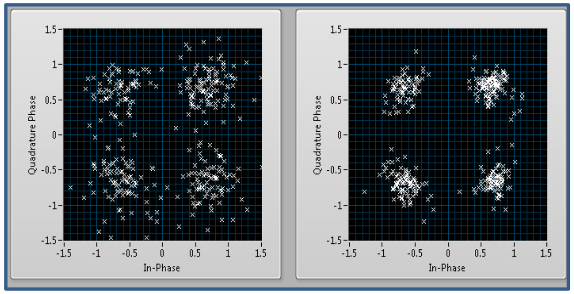
Determine static schedule, map to fixed-point data and arithmetic

Translate to hardware

Step	Calculation
1	$\hat{x}_j = 0$ $\tau_j^x(t) = (1-\pi)\gamma_X, \qquad \forall j \in \{1, ..., N\}$ $\hat{s}_i(t) = 0, \qquad \forall i \in \{1, ..., M\}$
2	$\tau_i^p(t) = \sum_j \lvert a_{ij}\rvert^2 \tau_j^x(t) = \sum_j \tau_j^x(t)$ $\hat{p}_i(t) = \sum_j a_{ij}\hat{x}_j(t) - \tau_i^p(t)\hat{s}_i(t-1)$ $= \mathbf{I}_\Omega \mathrm{FFT}(\hat{x}(t)) - \tau_i^p(t)\hat{s}_i(t-1)$
3	$\tau_i^s = \frac{1}{\gamma_B + \tau^p}, \qquad \forall i \in \{1, ..., M\}$ $\hat{s}_i(t) = \tau_i^s(t)\left(y_{\Omega i} - \hat{p}_i(t)\right)$
4	$\tau_j^r(t) = N\left[\sum_i \lvert a_{ij}\rvert^2 \tau_i^s(t)\right]^{-1}$ $\hat{r}_j(t) = \hat{x}_j(t) + \tau_j^r(t)\sum_i (a_{ij}^* \hat{s}_i(t))$ $= \hat{x}_j(t) + \tau_j^r(t)\mathrm{IFFT}\left(\mathbf{I}_\Omega^T \hat{x}(t)\right)$
5	$\eta_j = \frac{\pi}{1-\pi}\frac{\tau_j^r(t)}{\gamma_I + \tau_j^r(t)} \exp\left(\frac{\gamma_I \lVert\hat{r}_j(t)\rVert^2}{\tau_j^r(t)\left(\gamma_I + \tau_j^r(t)\right)}\right)$ $\rho_j = \frac{\eta_j}{1+\eta_j}$ $\hat{x}_j(t+1) = \frac{\gamma_I}{\gamma_I + \tau_j^r(t)}\rho_j \hat{r}_j(t)$ $\tau_j^x(t+1) = \eta\left[\frac{\tau_j^r(t)\gamma_I}{\gamma_I + \tau_j^r(t)} + \left(\frac{\gamma_I}{\gamma_I + \tau_j^r(t)}\right)^2 \lVert\hat{r}_j(t)\rVert^2 (1-\eta_j)\right]$
*	repeat steps 2-5 until convergence, resulting time-domain noise estimate: $\hat{x}_j(t+1)$

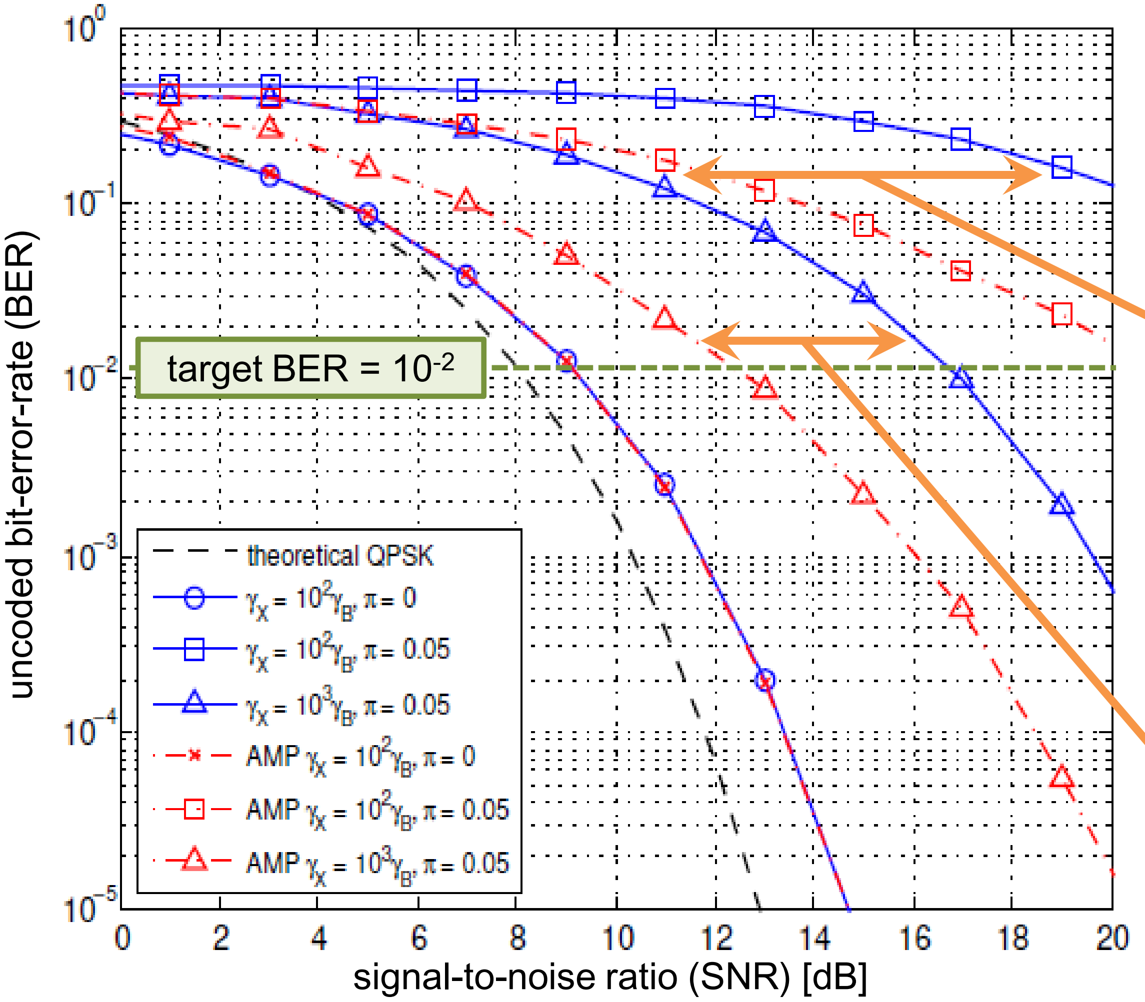


Inputs	Complex?	Length	Representation
π		1	U16.0
γ_X, γ_B		1	U16.-2
y_i	✓	128	2 × I16.1
Intermediates	**Complex?**	**Length**	**Representation**
$\hat{x}_j(t)$	✓	256	2 × I16.1
$\tau_j^x(t)$		256	U16.-2
$\hat{s}_i(t)$	✓	128	2 × I16.6
$\tau_i^p(t)$		1	U16.-5
$\hat{p}_i(t)$		128	2 × I16.0
τ_i^s		1	U16.0
$\tau_j^r(t)$		1	U16.-2
$\hat{r}_j(t)$	✓	256	2 × I16.2
η_j		256	U16.6
ρ_j		256	U16.6
Outputs	**Complex?**	**Length**	**Representation**
$\hat{x}_j(t+1)$	✓	256	2 × I16.1



Real-Time Measurements in Impulsive Noise

- Up to 8 dB of impulsive noise mitigated in real-time testbed



8 dB gain
for 30 dB
impulse power

4 dB gain
for 20 dB
impulse power

Cyclic Adaptive Modulation and Coding

- Rate maximized by solving

$$\mathbf{C}^\star = \arg\max_{\mathbf{C}\in\mathcal{C}} R(\mathbf{C})\mathbf{1}\left(Q(\mathbf{C},\mathbf{S}) \le p_b\right)$$

rate for a given map

theoretical SNR→BER

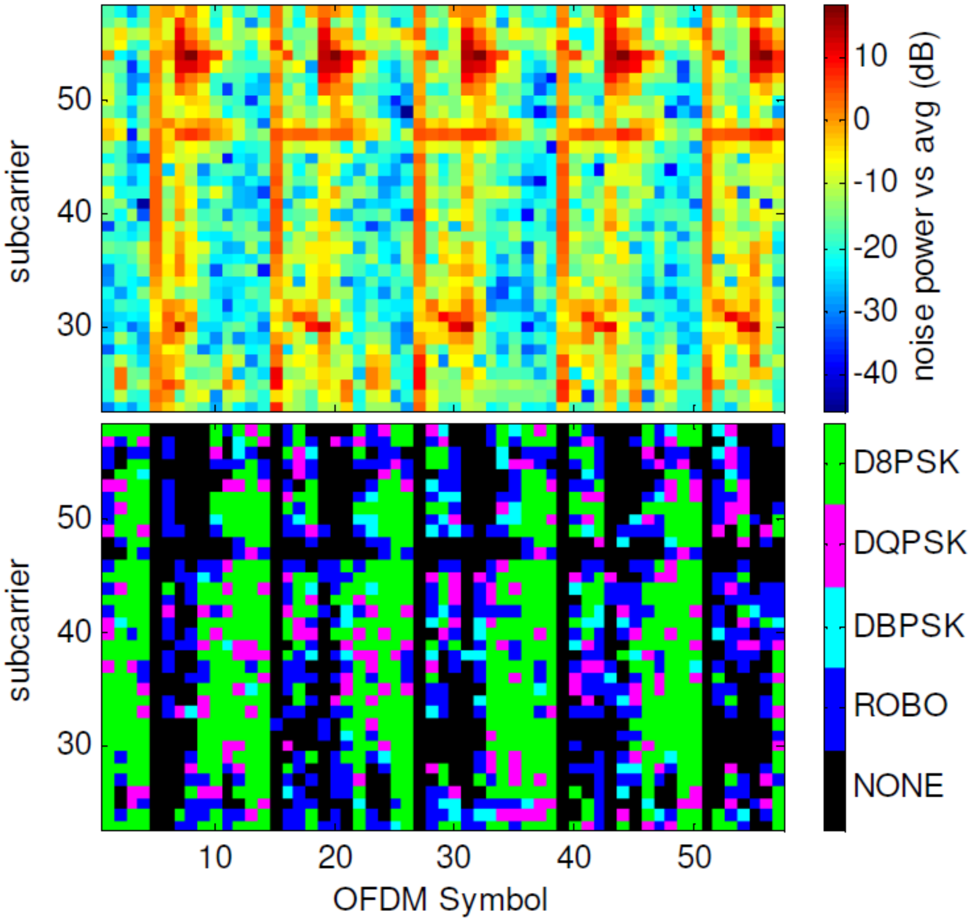
target BER

using SNR estimate $\mathbf{S}$

- Transmitter and receiver exchange tone map $\mathbf{C}^\star$
- Circularly index tone map

modulation	bits/subcarrier
D8PSK	3
DQPSK	2
DBPSK	1
ROBO	0.25

Example $\mathbf{S}$ and $\mathbf{C}^\star$ for G3-PLC in CENELEC-A (35.9-90.6 kHz) band



Simulations Using P1901.2 Noise Model

Case A

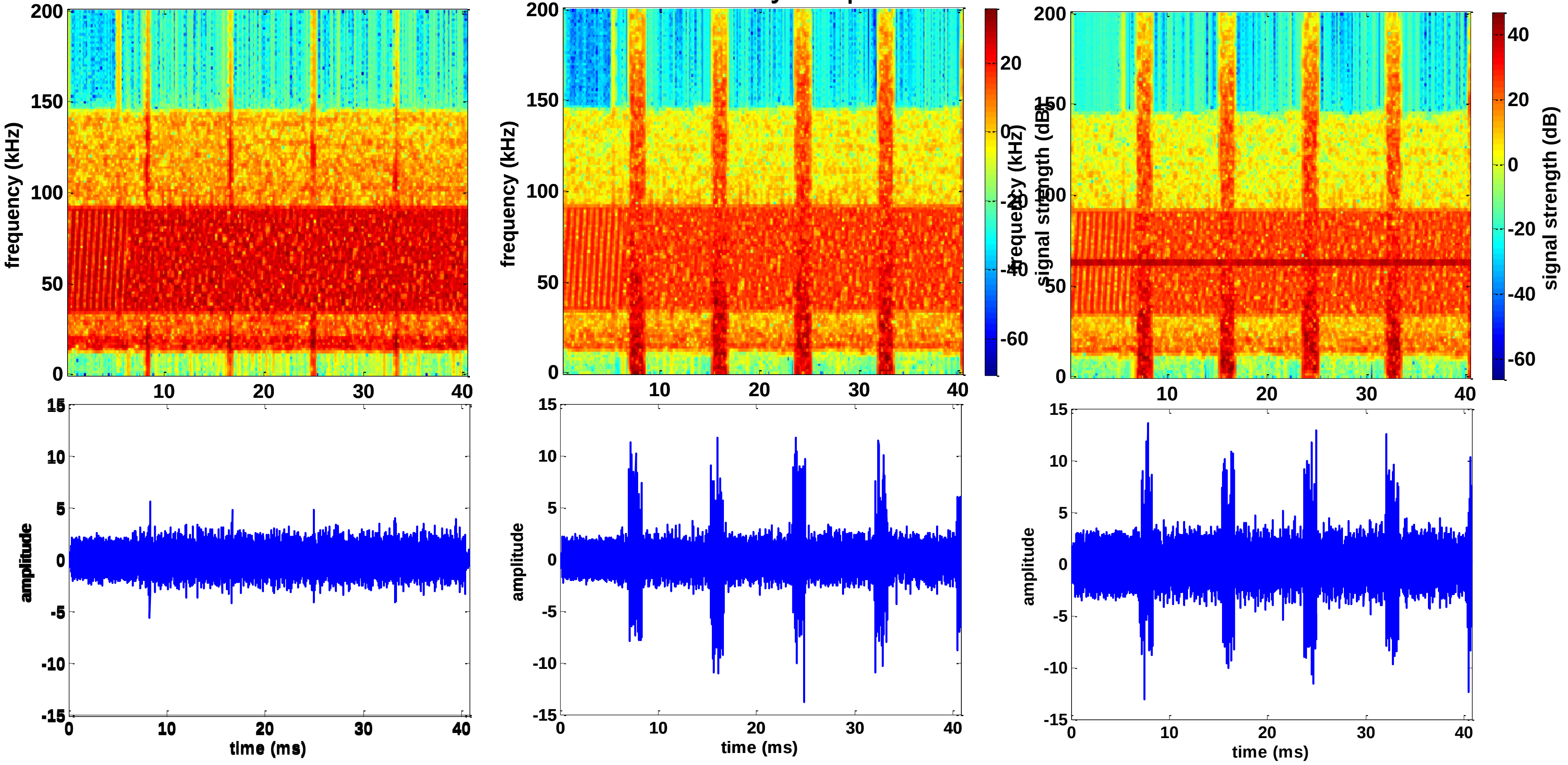
mild cyclic noise

Case B

moderate cyclic noise

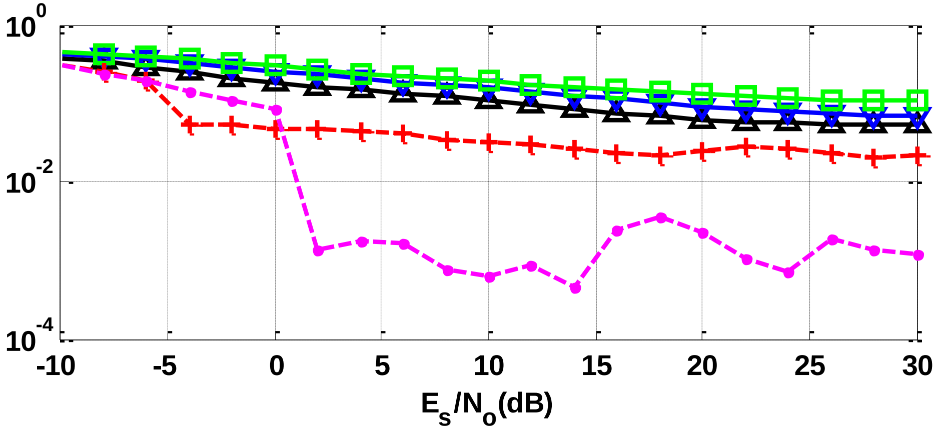
Case C

moderate cyclic noise +
narrowband noise



Case C: Cyclostationary + Narrowband Noise

uncoded BER



legend

- DBPSK
- DQPSK
- D8PSK
- CyclicLoading (p_b = 10^{-1})
- CyclicLoading (p_b = 10^{-2})

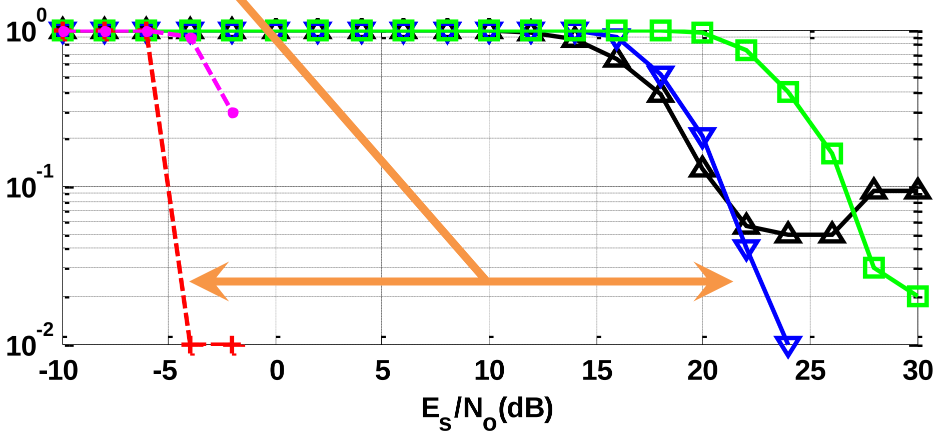
current

proposed

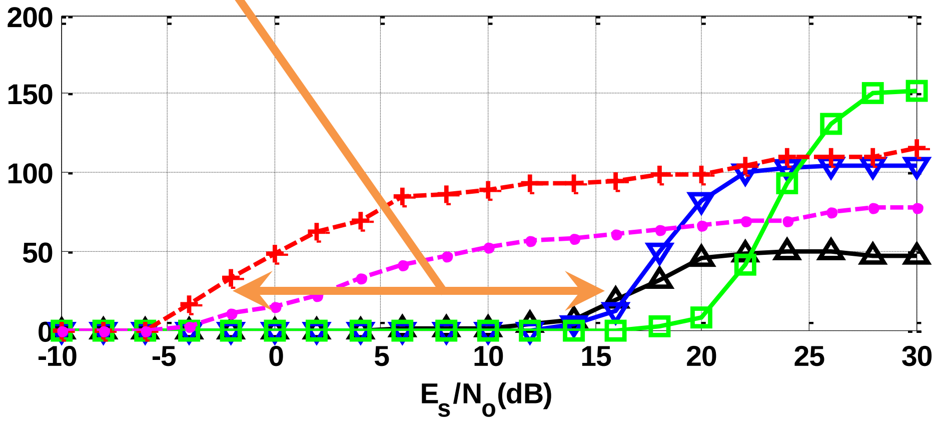
Can be used to achieve same throughput at 100x less transmit power

up to 28 dB operating point shift

coded BLER



raw throughput (kbps)



Contribution 2 Summary

Highlights
Conduct noise measurement campaign and cyclic spectral analysis
Implement real-time impulsive noise mitigation testbed for PLC
Develop cyclic adaptive modulation and coding scheme for OFDM
Achieved up to 8 dB noise mitigation in real-time and 28 dB operating point shifts

Relevant work

[Nie13a] – **K.F. Nieman**, J. Lin, M. Nassar, K. Waheed, and B.L. Evans, "Cyclic spectral analysis of power line noise in the 3-200 kHz band," *Proc. IEEE ISPLC*, 2013. **Won best paper award**

[Nie13b] – **K.F. Nieman**, M. Nassar, J. Lin, and B.L. Evans, "FPGA implementation of a message-passing OFDM receiver for impulsive noise channels. *Proc. IEEE Asilomar Conf. on Signals, Systems, and Computers*, 2013. **Won best student paper Architecture and Implementation Track**

[Wah14] – K. Waheen, **K. F. Nieman**, Adaptive cyclic channel coding for orthogonal frequency division multiplexed (OFDM) systems, US patent pending, 2014.

Third Contribution

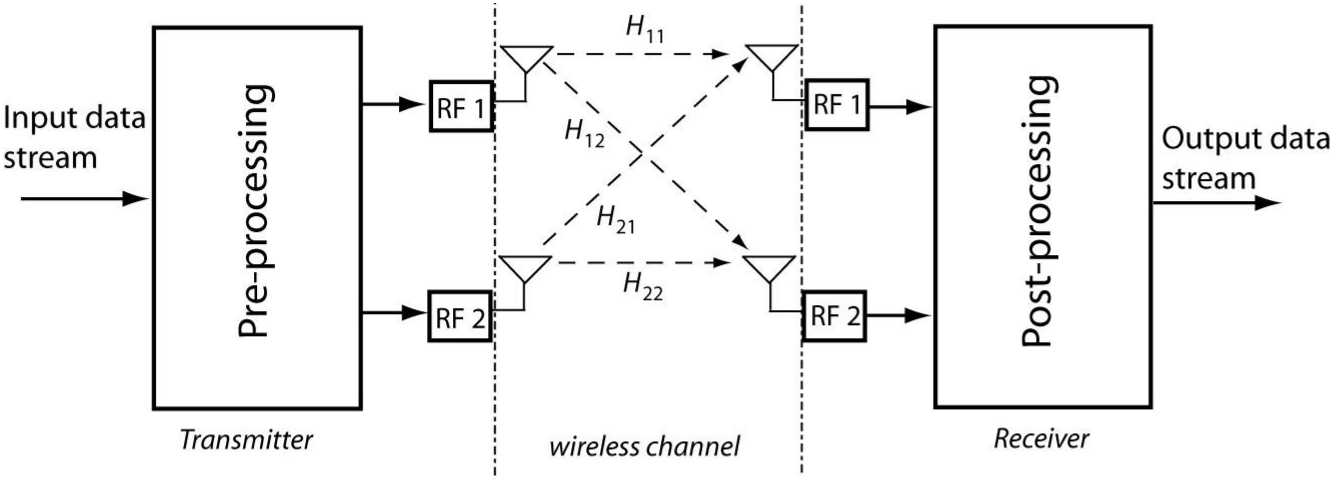
Space-Time-Frequency Methods for Multi-Antenna Cellular Communications

http://www.steelintheair.com/Cell-Phone-Tower.html

Multiple-Input, Multiple-Output (MIMO)

- Multiple antennas at transmitter and/or receiver
  - Higher robustness via space-time block codes
  - Increased rate via spatial multiplexing
- Can be extended to multi-user MIMO (MU-MIMO)
  - Serve multiple simultaneous users via spatial-division multiple access
  - Over same bandwidth, same time slot, just more antennas

MIMO system

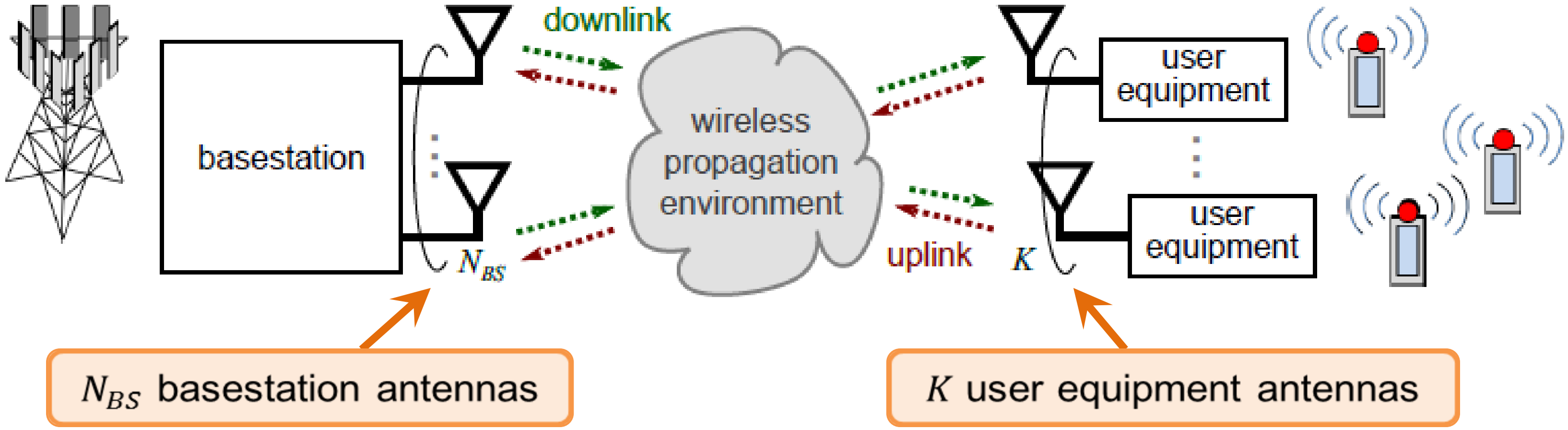


$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}$$

Matrix channel

Multiplexing performance is highly dependent on propagation conditions[Rus13]

Massive MIMO (Scaling Up MU-MIMO)



N_{BS} basestation antennas

K user equipment antennas

- Scale N_{BS} by an order of magnitude over existing standards
  - LTE-A provisions $N_{BS} \leq 8$, so increase to $N_{BS} = 64, 100, 128$
- Challenges for Massive MIMO
  - Scaling data rates and interfaces to support large N_{BS}
  - Low-latency for channel reciprocity (fast switch from uplink to downlink)
  - Synchronizing radios across N_{BS} basestation antennas

Existing Massive MIMO Testbeds

- Several research groups have developed test systems

Group	Band (GHz)	Hardware Platform	Number of Antennas at Basestation	Number of Users	Real-time MIMO Processing?
Lund University [Rus13]	2.6	Network Analyzer	128 cylindrical array	6	No[1]
Rice University [She12]	2.4	WARP boards, powerPC	8 x 8 = 64 planar array	15	No[2]
Samsung FD-MIMO [Sam13]	<5	Proprietary w/ Freescale DSPs	8 x 8 = 64 planar array	?	Yes[3]

[1] Data collected over long duration (hours) where channel is assumed constant; post-processed.

[2] Experimental results based on SINR measured at UE w/ high latency (100 ms) beamforming over 0.625 MHz of bandwidth. Currently working on lower latency, higher BW system.

[3] Proprietary system; not many public details available except that 1 Gb/s achieved at 2 km.

Proposed Massive MIMO Test Platform

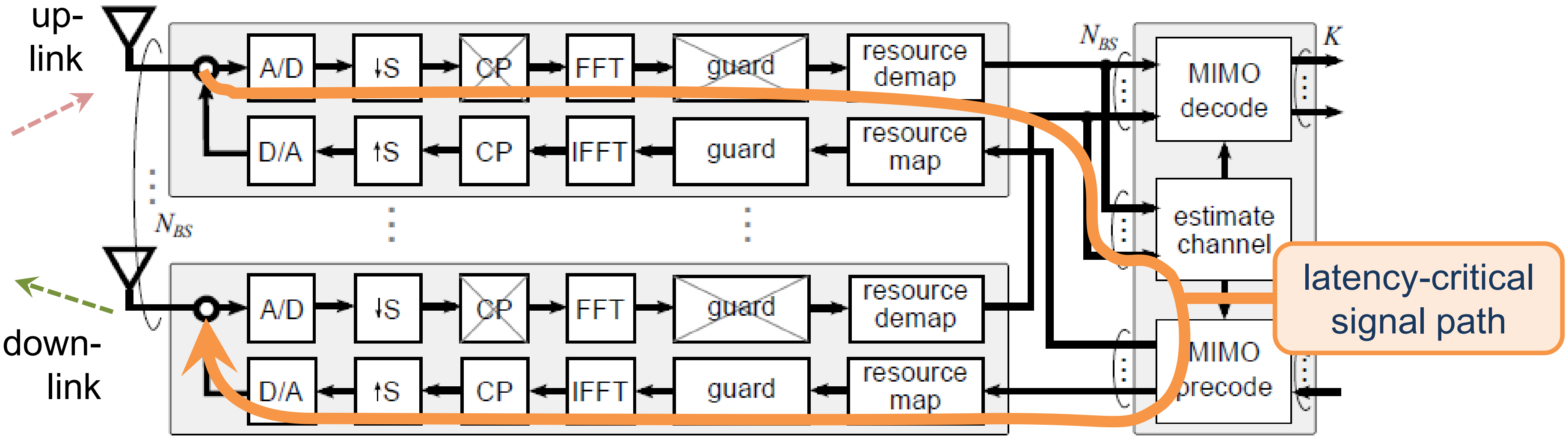
- New platform allows for real-time, off-the-shelf solution

Group	Band (GHz)	Hardware Platform	Number of Antennas at Basestation	Number of Users	Real-time MIMO Processing?
Lund University [Rus13]	2.6	Network Analyzer	128 cylindrical array	6	No
Rice University [She12]	2.4	WARP boards, powerPC	8 x 8 = 64 planar array	15	No
Samsung FD-MIMO [Sam13]	<5	Proprietary w/ Freescale DSPs	8 x 8 = 64 planar array	?	Yes
Proposed	1.2-6	National Instruments USRP	Up to 128	10	Yes[1]

[1] 20 MHz bandwidth w/ less than 1 ms latency.

Channel State Acquisition and Processing

Processing at the basestation

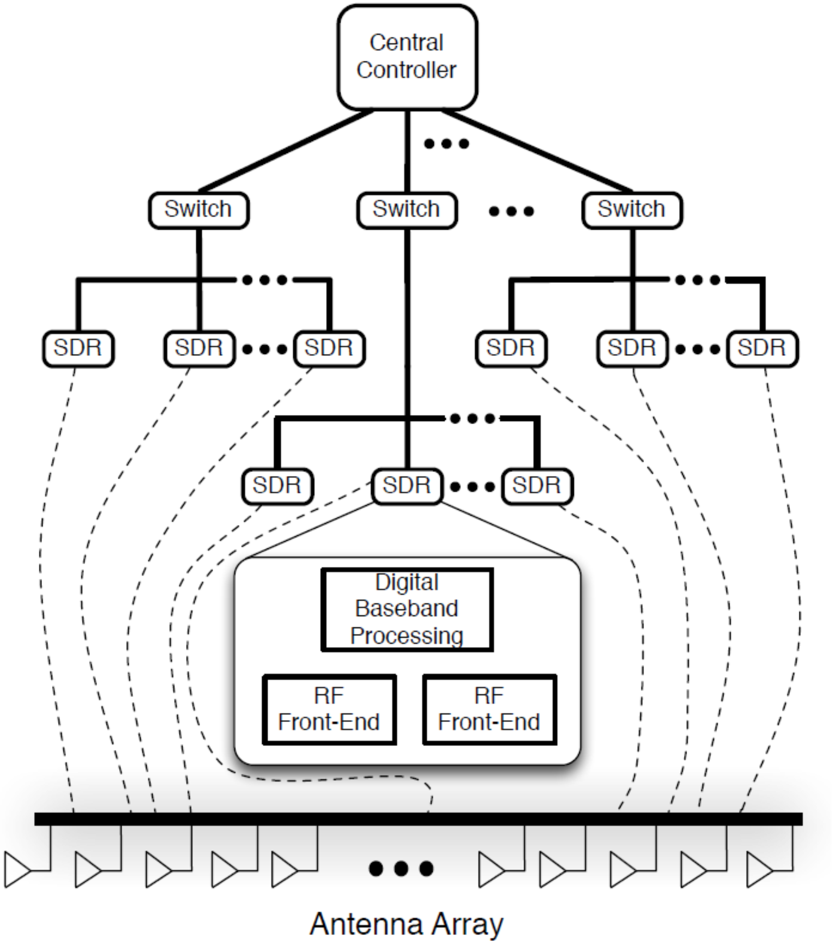


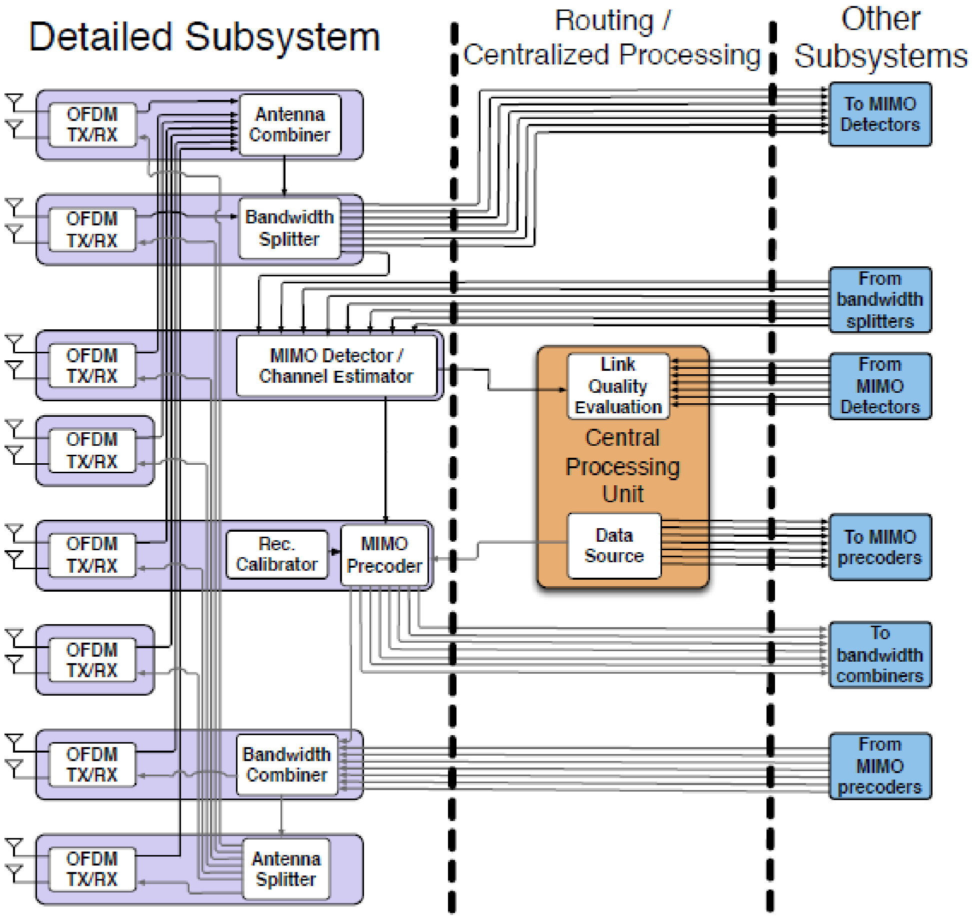
- Supports different precoders – zero-forcing, MRT, etc.
- Uses OFDM signaling in uplink and downlink
  - Divide processing via orthognal sub-bands to meet hardware limitations
- Assumption of channel reciprocity requires:
  - Fast switching between uplink and downlink (< channel coherence time)
  - Compensation of RF impairments (transmit and receiver response)

Mapping to Hardware

star architecture links processing elements (FPGAs) via PCI-Express

distributed MIMO processing over 16-antenna subsystems





Lund University (100-Antenna) Testbed

160-element dual-polarized array allows different geometries to be explored

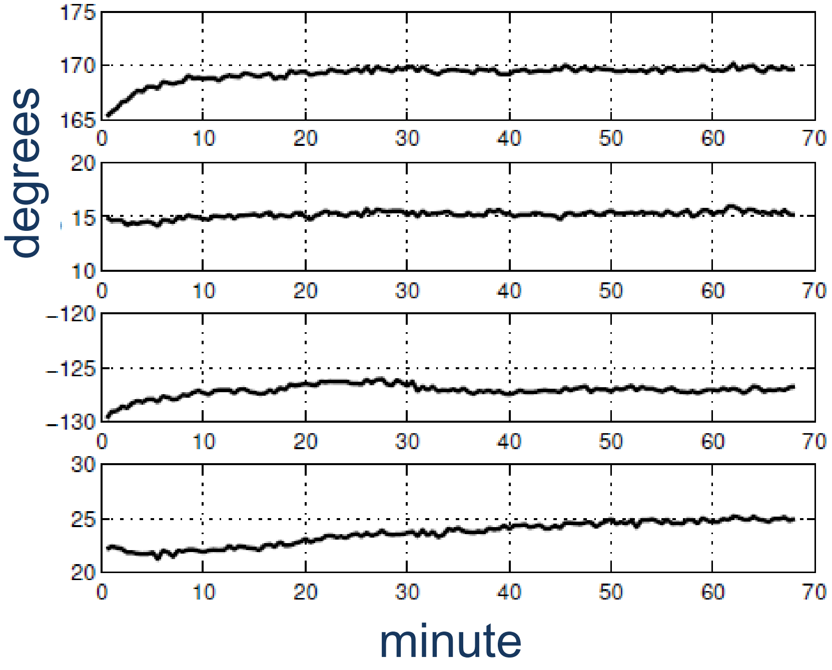
cabled PCI-Express to switches and controller

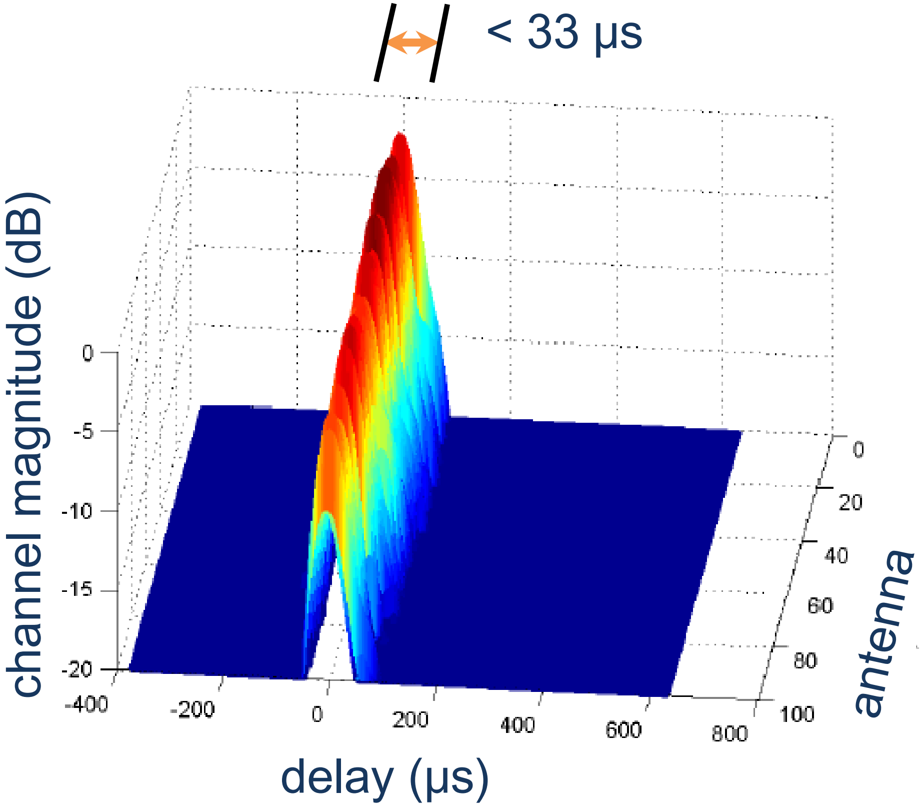
distributed processing of
120 MS/s
* 32 bits/S/channel
* 100 channels
= 384 Gb/s in uplink and downlink directions

Phase and Time Synchronization Results

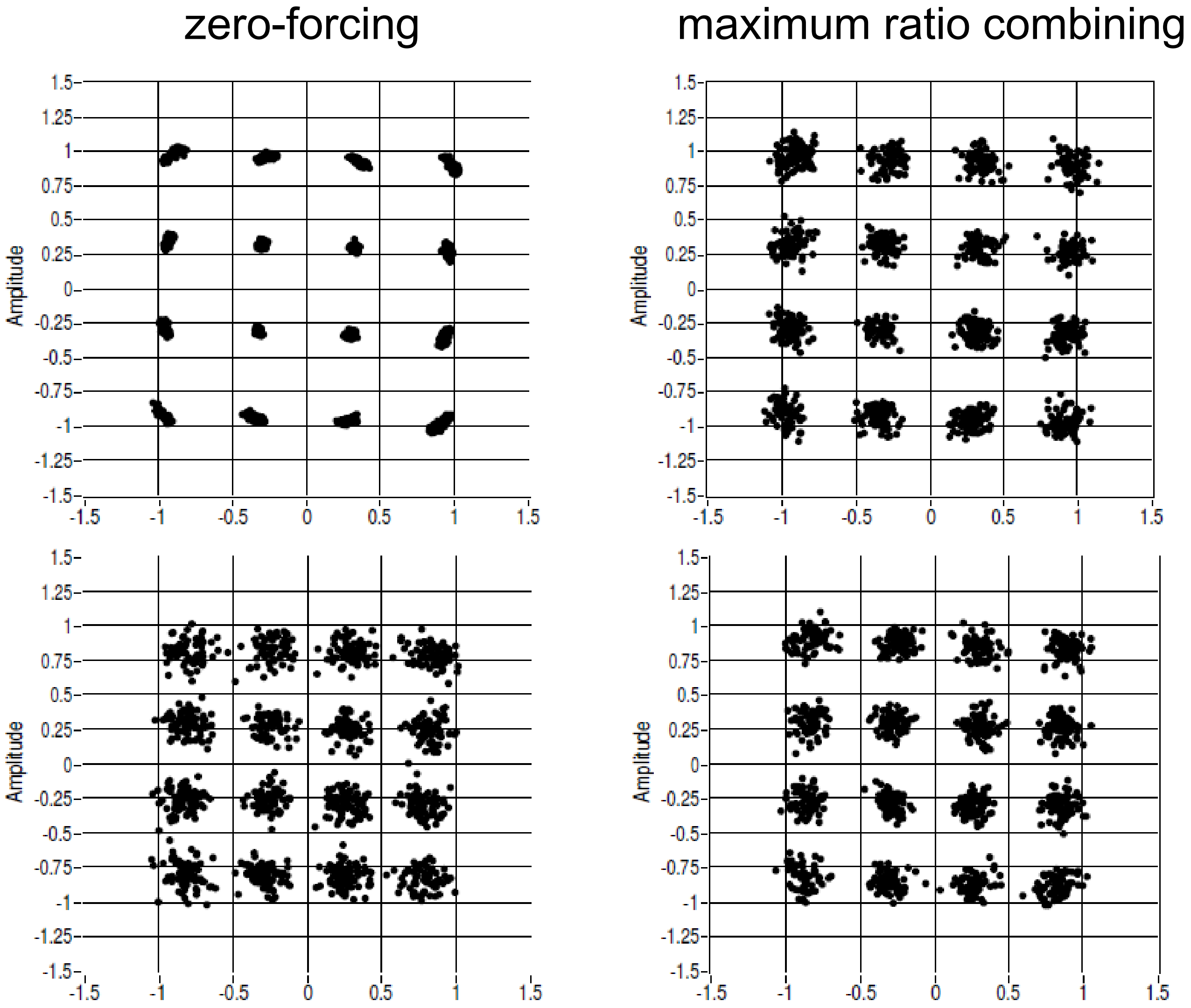
phase coherency between RF channels <5° over 1 hr

100-antenna wireless channel sounding reveals synchronization within one 30.72 MS/s sample (33 µs)





100-Antenna Uplink MIMO Constellation



zero-forcing

maximum ratio combining

line-of-sight,
~2 m spacing
between users

non-line-of-sight,
~10 cm spacing
between users

Contribution 3 Summary

Highlights
Develop a commercial, off-the-shelf solution for up to 128-antenna MIMO
Scale data rates/interfaces, minimize latency, and distribute synchronization
Presented first results of 100-antenna MIMO

Relevant work

[Nie13] – **K. F. Nieman** and B. L. Evans, "Time-Domain Compression of Complex-Baseband LTE Signals for Cloud Radio Access Networks", *Proc. IEEE Global Conference on Signal and Information Processing*, 2013.

[Hua12] – H. Huang, **K. Nieman**, P. Chen, M. Ferrari, Y. Hu, and D. Akinwande, "Properties and applications of electrically small folded ellipsoidal helix antenna", *IEEE Antennas and Wireless Propagation Letters*, 2012.

[Hua11] – H. Huang, **K. Nieman**, Y. Hu, and D. Akinwande, "Electrically small folded ellipsoidal helix antenna for medical implant applications", *Proc. IEEE International Symposium on Antennas and Propagation*, 2011.

[Vei14] – J. Vieira, S. Malkowsky, **K. F. Nieman**, Z. Miers, N. Kundargi, L. Liu, I. Wong, V. Owall, O. Edfors, and F. Tufvesson, "A flexible 100-antenna testbed for Massive MIMO", *Proc. IEEE Global Communication Conference (GLOBECOM)*, 2014, accepted for publication.

[Nie14] -- **K. F. Nieman**, N. U. Kundargi, I. C. Wong, and B. C. Prumo, Synchronization of large antenna count systems”, 2014, US patent pending.

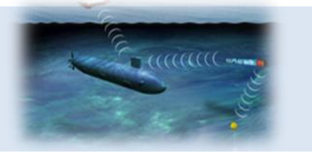
[Won14] – I. C. Wong, **K. F. Nieman**, and N. U. Kundargi, “Signaling and frame structure for Massive MIMO cellular telecommunication systems”, 2014, US patent pending.

[Kun14] – N. U. Kundargi, I. C. Wong, and **K. F. Nieman**, Distributed low latency Massive MIMO telecommunication transceiver processing framework and use," 2014, US patent pending

[Nie14] – **K. F. Nieman**, N. Kundargi, I. Wong, and B. L. Evans, "High speed processing framework for high channel count MIMO", *Proc. IEEE ISCAS*, 2014, to be submitted.

Summary of Contributions

Multi-dimensional signal processing methods can be applied to dramatically enhance communication performance <u>without</u> sacrificing real-time requirements.

Contribution	Highlights
	Space-time reverberation (interference) reduction method
	Demonstrate 10x higher sum rates than prior state-of-the-art
	Measure cyclic noise and develop cyclic modulation and coding
	Implement real-time impulsive noise mitigation testbed
	Demonstrate up to 8 dB noise mitigation and 28 dB operating point shifts
	Develop a commercial, off-the-shelf solution for up to 128-antenna MIMO
	Scale rates/interfaces, minimize latency, and distribute synchronization
	Presented first results of 100-antenna MIMO

Summary of Relevant Work by Presenter

[Nie10a] – K.F. Nieman, K.A. Perrine, T.L. Henderson, K.H. Lent, T.J. Brudner, and B.L. Evans, Wideband monopulse spatial filtering for large receiver arrays for reverberant underwater communication channels. *Proc. IEEE OCEANS*, 2010.

[Per10] – K.A. Perrine, K.F. Nieman, T.L. Henderson, K.H. Lent, T.J. Brudner, and B.L. Evans. Doppler estimation and correction for shallow underwater acoustic communications. *Proc. IEEE Asilomar Conference on Signals, Systems, and Computers*, 2010.

[Nie10b] – K.F. Nieman, K.A. Perrine, K.H. Lent, T.L. Henderson, T.J. Brudner, and B.L. Evans. Multi-stage and sparse equalizer design for communication systems in reverberant underwater channels. *Proc. IEEE Workshop on Signal Processing Systems*, 2010.

[Nie11] – K. F. Nieman, K. A. Perrine, T. L. Henderson, K. H. Lent, and T. J. Brudner, "Sonar array-based acoustic communication receivers with wideband monopulse processing," *USN Journal of Underwater Acoustics*, 61(2), 2011.

[Hua11] – H. Huang, K. Nieman, Y. Hu, and D. Akinwande, "Electrically small folded ellipsoidal helix antenna for medical implant applications", *Proc. IEEE International Symposium on Antennas and Propagation*, 2011.

[Hua12] – H. Huang, K. Nieman, P. Chen, M. Ferrari, Y. Hu, and D. Akinwande, "Properties and applications of electrically small folded ellipsoidal helix antenna", *IEEE Antennas and Wireless Propagation Letters*, 2012.

[Nie13a] – K.F. Nieman, Jing Lin, M. Nassar, K. Waheed, and B.L. Evans, "Cyclic spectral analysis of power line noise in the 3-200 kHz band," *Proc. IEEE Conf. on Power Line Communications and Its Applications*, 2013. **Won best paper award**

[Nie13b] – K.F. Nieman, M. Nassar, Jing Lin, and B.L. Evans, "FPGA implementation of a message-passing OFDM receiver for impulsive noise channels. *Proc. IEEE Asilomar Conf. on Signals, Systems, and Computers*, 2013. **Won best student paper Architecture and Implementation Track, took 2nd place overall**

[Nie13c] – K. F. Nieman and B. L. Evans, "Time-Domain Compression of Complex-Baseband LTE Signals for Cloud Radio Access Networks", *Proc. IEEE Global Conference on Signal and Information Processing*, 2013.

[Vei14] – J. Vieira, S. Malkowsky, K. F. Nieman, Z. Miers, N. Kundargi, L. Liu, I. Wong, V. Owall, O. Edfors, and F. Tufvesson, "A flexible 100-antenna testbed for Massive MIMO", *Proc. IEEE Global Communication Conference (GLOBECOM)*, 2014, accepted for publication.

[Nie14] –K. F. Nieman, N. Kundargi, I. Wong, and B. L. Evans, "High speed processing framework for high channel count MIMO", *Proc. IEEE International Symposium on Circuits and Systems (ISCAS)*, 2014, to be submitted.

[Nie14] -- K. F. Nieman, N. U. Kundargi, I. C. Wong, and B. C. Prumo, Synchronization of large antenna count systems", 2014, US patent pending.

[Won14] – I. C. Wong, K. F. Nieman, and N. U. Kundargi, "Signaling and frame structure for Massive MIMO cellular telecommunication systems", 2014, US patent pending.

[Kun14] – N. U. Kundargi, I. C. Wong, and K. F. Nieman, Distributed low latency Massive MIMO telecommunication transceiver processing framework and use," 2014, US patent pending

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Questions?