An Acoustic-Electric Bridge: Traversing Metal Barriers Using Ultrasound

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Background
Remote Sensing Applications

Internal Sensors

External Sensors

Monitoring

Actuation

Control

Metallic Chambers
The Prevalent Solution

Introduce barrier penetrations & cable feed-throughs

Cables used for power and data transmission

...must eliminate need for penetrations which can limit structural integrity & environmental isolation...
Quintessential Scenario: Submarines

Real-Time System Monitoring Through Bulkheads
Alternative “Wireless” Approach

Ultrasound propagates well through metals

Use ultrasonic transducers to make an acoustic-electric transmission channel

Electromagnetic Acoustic Transducers (EMATs)
- Barrier contact not required
- Bulky & inefficient

Piezoelectric Transducers
- Efficient, high energy density
- Require barrier contact
First high-performance real-time system capable of simultaneous data and power transmission through thick metal barriers using ultrasound.

Reliable, robust, non-destructive alternative to prevalent solutions.

Mitigate Risks: sensitive applications

Reduce Costs: installation, inspection, maintenance

Provide Platform: enable a wide range of new applications
Solution: The Acoustic-Electric Bridge

[Diagram of the Acoustic-Electric Bridge]

- **Piezoelectric Disk Transducers**
- **Metallic Barrier**

[Diagram of Electromagnetic and Ultrasonic Wave Conversion]

- **Electromagnetic Wave**
  - Electric Field
  - Magnetic Field

- **Ultrasonic Pressure Wave**
  - Conversion

- **Electromagnetic Wave**
System Overview

2.5” thick segment of steel submarine hull used as barrier

Separate Power & Data Channels

- Power: 2.625” diameter, 1 MHz
- Data: 1” diameter, 4 MHz
- 1” separation edge-to-edge
Power Channel Response

Simultaneous conjugate power matching applied

42.7 % efficiency predicted @ 1.102 MHz
Continuous Wave (CW) Power Transfer

Create a CW power signal for transmission

Apply received CW power signal to load

Simultaneous conjugate power matching

100 W PA

50.12 W of AC power @ 1.1 MHz to a 50 Ω load (51 % efficiency)
CW Power Demo: 25 W Light Bulb
Creating a DC Power Supply

Add rectification to convert CW signal to DC (e.g., a full-wave rectifier)

19.22 watts of DC power ($31 \ V_{DC}$) extracted from 1.1 MHz CW signal

Diode losses and internal capacitances reduce system efficiency
When transmitting bursts of information, interfacial reflections cause reverberation.

Signal energy spreads out over time (via echoes) and causes inter-symbol interference (ISI).
4 MHz Data Channel: Measured Response

Targeted bandwidth: 2.083 MHz – 6.250 MHz

Normalized (Unit Energy) Impulse Response vs. Time

Delay Spread: 150 μs

|S₂₁|² vs. Frequency

Coherence BW: 6.67 kHz

Very frequency-selective channel makes conventional pulsed & single-carrier communication schemes difficult
A powerful multi-carrier solution:

Orthogonal Frequency-Division Multiplexing (OFDM)

- Large number of orthogonal signals
- Keep individual signal bandwidths small
- Keep individual data rates below coherence BW
- Adapt to channel response
- Achieve large aggregate data rate and high spectral efficiency through parallelization

Significant Advantage:
OFDM allows for high rates even in non-ideal acoustic-electric channels
Sub-carrier Data Modulation Scheme: QAM

M-ary Square Quadrature Amplitude Modulation with Gray-Coding:

Carrier-Suppressed Symbol Constellations

4-QAM (2 bits) $\rightarrow$ 256 QAM (8 bits)

Strings of data bits are encoded as sub-carrier amplitudes & phase combinations

Reduced symbol separation increases sensitivity to noise & ISI
Fundamental OFDM DSP Architecture

Transmitter

DIGITAL INPUT: Serial Stream of Binary Data
Symbol Encoder
Time-Division Demultiplexer
Complex Inverse Fast Fourier Transform (IFFT)
Complex Modulator
DAC
ANALOG OUTPUT: OFDM TX Signal

Receiver

ANALOG INPUT: OFDM RX Signal
ADC
Complex Demodulator
90°
Complex Fast Fourier Transform (FFT)
Time-Division Demultiplexer
Symbol Decoder
DIGITAL OUTPUT: Serial Stream of Binary Data
Aggregate system bandwidth: 2.083 MHz – 6.250 MHz (4.167 MHz)

4096 sub-carriers, 1.017 kHz sub-carrier separation
Data Transmission Link Hardware
Performance Optimization: QAM Bit-Loading

Estimated Signal-to-Noise-and-Distortion (SNDR) Ratio

- Start with target aggregate bit-error rate (BER)
- Pack more/fewer bits into stronger/weaker sub-carriers

System was able to achieve 17.4 Mbps with a BER of 10^{-6}
Enabling Simultaneous Power & Data

Power and data signal levels can differ by as much as 7 orders of magnitude.

Close proximity: 1” channel separation

System has to mitigate power-to-data interference

Challenges

1. Fundamental power signal leakage
2. Harmonic power signal leakage
3. Interferer energy spreading
Mitigating Effects of Power Leakage

1. Prevent power leakage from saturating OFDM RX path
2. Reduce in-band power signal harmonics to tolerable levels
3. Synchronize CW power signal with clock used to generate sub-carriers to localize leakage to single FFT bins

Simple solution: don’t use any sub-carriers corrupted by the power harmonic leakage (at most 4 out of 4096) for a negligible hit on data link rate

Simultaneous ≈ 17.40 Mbps & 50 W Transmission
Complete System Hardware

**COTS Components & Evaluation Boards**

**DATA LINK**  
- Xilinx Virtex-6 FPGA (DSP)
- 14-bit DAC
- TX Signal Processing
- Matching Networks, Rectifier, Regulator
- 25 W Light Bulb

**POWER LINK**  
- 12-bit ADC
- RX Signal Processing
- 100 W PA
- Harmonic Rejection Filter & Matching Network
Global Impacts
Many Fields of Application

Tremendous improvement in system cost and safety

Provides a pathway for novel systems and applications
Overview & Primary Takeaways

Short Term
- Build consumer confidence
- Miniaturize System
- Low-hanging fruit
- Field Testing
- Driven by Defense & Energy

Long Term
- Seamless modular platform
- Co-development with new sensor technologies
- Defense, Energy, Aerospace, Industrial, Chemical Processing, Maritime, and many more
Challenges Facing Development of a Generic Platform

Capacity

Gbps data / kilowatt power capabilities
Limits of Data Throughput

Estimated Signal-to-Noise-and-Distortion (SNDR) Ratio

Using Shannon-Hartley Theorem:

\[ C_{\text{max}} = \sum_{n=1}^{N} \Delta f \cdot \log_2(1 + \text{SNDR}_n) \]

Maximum Channel Capacity is 48.0 Mbps
(11.52 bits/s/Hz)
Achieving Gbps Links

Low-Hanging Fruit
- Bit & Power Loading
- Source & Channel Coding
- Reduce Hardware Noise
- ↑ Frequency / BW

Multiple Channels
- Closely Packed
- Interference Cancellation
- Joint Detection

Enable Bi-directional Data Links
Limits of Power Transmission

**Power Sweep Measurements**

![Graph showing power delivered to 50Ω load vs. estimated power applied to channel]

**Very linear channel & system behavior**

PA output power is only immediate limitation → kW transfer is feasible
Challenges Facing Development of a Generic Platform

- Many variable factors in channel formation
- Reliability
- Capacity: Gbps data / kilowatt power capabilities
Data Channel Sensitivity: Couplant

Modeled Frequency Response of the Channel vs. Epoxy Layer Thickness

Very low sensitivity – high data throughput regardless of bonding
Data Channel Sensitivity: Barrier

Modeled Frequency Response of the Channel vs. Steel Barrier Thickness

Channel capacity is nearly independent of barrier thickness above 2 mm
Power Channel Sensitivity

Acoustic Beam in Semi-Infinite Barrier

Increasing Transducer Diameter

→ Grain Scattering → Non-Uniformity → Bonding Layer Quality

Diffraction Losses:

Keeping power efficiency high across various applications will be a significant challenge
Challenges Facing Development of a Generic Platform

- Many variable factors in channel formation
- Gbps data / kilowatt power capabilities
- Reliability
- Size
- Miniaturization of internal & external electronics
- Capacity
System Miniaturization

Data Link:
less complexity than a cell phone
custom board/ASIC

Power Link:
heat dissipation
large currents/voltages
Challenges Facing Development of a Generic Platform

- Many variable factors in channel formation
- Miniaturization of internal & external electronics
- Gbps data / kilowatt power capabilities
- Common interface standards, “plug & play”
Black Box Design Approach

Automatic calibration, adaptive tracking of physical & environmental changes, redundancy & fail-safes
Conclusions
The Take-Aways

- Novel technology for non-destructively relaying power and data signals efficiently across thick metal walls.
- Potential to significantly reduce costs, improve safety, and maintain system integrity & isolation.
- Diverse range of applications - generic modular transmission platform.
- Some technical hurdles lie ahead, but good engineering should address these.
Barriers Prevent Wireless Sensing

Metal exhibits Faraday shielding

Conventional electromagnetic wireless technologies are not viable
Simulated (FEM) steady-state pressure distribution in channel:

(axi-symmetric simulation; transducer thickness λ/2 at resonance)
Underwater Detectability (Stealth)
Cyclic Prefix

Temporal guard interval lasting at least as long as the channel’s delay spread to mitigate ISI

Sample OFDM Word

Sample OFDM Word with Added Cyclic Prefix

Redundant information adds overhead (can be kept small with careful design considerations)
Sub-carrier Modulation Scheme: PSK

M-ary Phase Shift Keying with Gray-Coding:
Strings of data bits are encoded as discrete sub-carrier phases

- Smaller symbol separation increases sensitivity to noise & ISI
- Simple encoding & decoding since amplitude scaling has no effect
Performance Optimization: PSK Bit-Loading

Estimated Signal-to-Noise-and-Distortion (SNDR) Ratio

- Start with target aggregate bit-error rate (BER)
- Pack more/fewer bits into stronger/weaker sub-carriers

System was able to achieve 12.4 Mbps with a BER of $10^{-6}$
Extrapolation of Power Capabilities

- Construct or purchase a PA with higher output power
  - kW range could be very useful for active sonar applications
- Multiple parallel sets of transducers with one or multiple PAs
- Pre-stress transducers (compressive strength > tensile strength)
- Eliminate electrical insulation layer on power transducers
- Reduce material damping in transducers (piezoelectric material selection)
- Minimize acoustic couplant layer thickness (epoxy)

FEM Simulation Results Showing Projected Improvements for 0.375” Hull:

Maximum Simulated Power Transfer Efficiencies:
Current System: $\eta \approx 60\%$
Optimized System: $\eta \approx 90\%$
Channel Modeling: Acoustic Layers

2-port acoustic network:

\[ \frac{\partial^2 u}{\partial z^2} = \frac{\rho}{E} \frac{\partial^2 u}{\partial t^2} \]

\[ c_s = \sqrt{\frac{E}{\rho}} \]

- \( u \) – particle displacement
- \( c_s \) – speed of sound

\[
\begin{bmatrix}
F_1 \\
v_1
\end{bmatrix} =
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
F_2 \\
v_2
\end{bmatrix}
\]

\[
\vec{a}_{\text{slab}} =
\begin{bmatrix}
\cosh(\gamma d) & Z \sinh(\gamma d) \\
Z^{-1} \sinh(\gamma d) & \cosh(\gamma d)
\end{bmatrix}
\]

Transmission Line (Telegrapher’s Equations)

\( v \) – particle velocity
\( F \) – force on particle
Channel Modeling: Piezoelectric Layers

3-port acoustic-electric network:

Constitutive Piezoelectric Equations

\[ T = c_{33}^D S - h_{33} D, \]
\[ \mathcal{E} = -h_{33} S + \beta_{33}^S D, \]

Boundary condition on back mechanical face \((Z_b)\)

Incorporating Loss

Acoustic-Electric 2-port ABCD parameters

\[
\begin{bmatrix}
F_1 \\
F_2 \\
V_3
\end{bmatrix} =
\begin{bmatrix}
-Z\coth(\gamma d) & Z\csch(\gamma d) & -\frac{h_{33}}{j\omega} \\
-Z\csch(\gamma d) & Z\coth(\gamma d) & -\frac{h_{33}}{j\omega} \\
\frac{h_{33}}{j\omega} & \frac{h_{33}}{j\omega} & \frac{1}{j\omega c_0}
\end{bmatrix}
\begin{bmatrix}
v_1 \\
v_2 \\
I_3
\end{bmatrix}
\]

\[
\begin{bmatrix}
V \\
I
\end{bmatrix} =
\begin{bmatrix}
A_{TX} & B_{TX} \\
C_{TX} & D_{TX}
\end{bmatrix}
\begin{bmatrix}
F \\
v
\end{bmatrix}
\]
Transformer Model

7-Element Transformer Equivalent Circuit:

- $L_a$ – Primary Winding Leakage Inductance
- $R_a$ – Primary Winding Loss
- $L_b$ – Secondary Winding Leakage Inductance
- $R_b$ – Secondary Winding Loss
- $L_m$ – Magnetizing (Mutual) Inductance
- $R_m$ – Magnetic Loss
- $\Phi$ – Effective Turns Ratio
Full Channel Model

\[ \vec{d}_{CH} = \vec{d}_{TFMR,DN} \cdot \vec{d}_{P1} \cdot \vec{d}_{C1} \cdot \vec{d}_{M} \cdot \vec{d}_{C2} \cdot \vec{d}_{P2} \cdot \vec{d}_{TFMR,UP} \]
Channel Model vs. Measurements

Excellent Correlation Across Data Transmission Bandwidth