Analog and Digital Signal Processing

New Solution to Air-Data Transmission Using Low-Cost Narrow-Band Ultrasonic Transducers

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Problem statement:

To find a way around short distance (up to 15 m) data communication limitations

What are these limitations?

- Electromagnetic communication: Highly susceptible to jamming (intentional or non-intentional)
  Easily located and tracked (traceability)
  It can be “taped (recorded)“ from a close or remote location
- Light-waves (laser, infra-red…): Often impractical (line-of-sight) or not allowed (operating room)
  Highly vulnerable to smoke or air contamination

The proposed solution: ultrasonic air-data transmission

What does it bring compared to electromagnetic or light-waves?

Highly secure pre-authentification - untraceable transmission (useful for security patrol)

Transmission strictly confined in a well defined area (no "through-the-wall" transmission)

Some conditions for this solution to be useful:
5-10 kbps over distances up to 15 m
Robustness regarding "multi-paths"
Low-power requirement and low-cost

Presentation outline:

1. Time Domain Response Shaping
2. Choosing the Right Modulation
3. Data Modulated Driving Signal
4. Receiver Structure
5. Computer Simulations
6. Experimental Results
7. Conclusions

1. Time Domain Response Shaping

The problem:

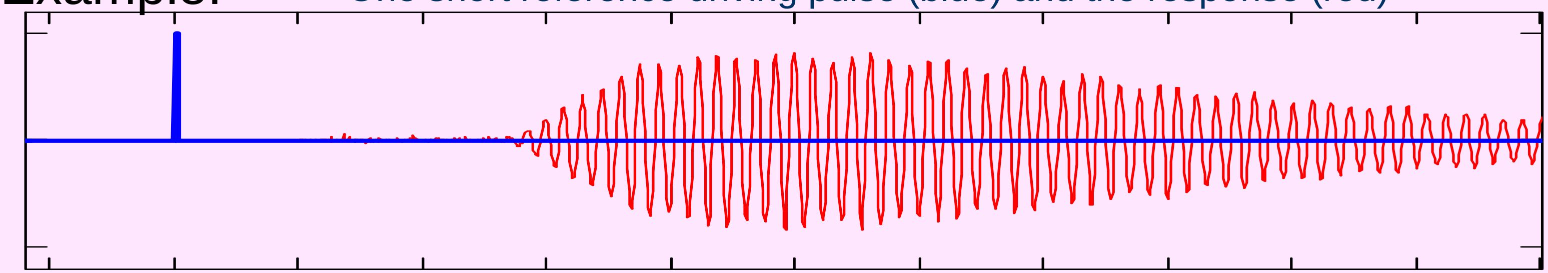
Narrow bandwidth of low-cost 40 kHz transducers
➔ Very long impulse response ➔ Limited data rate of transmission

The solution:

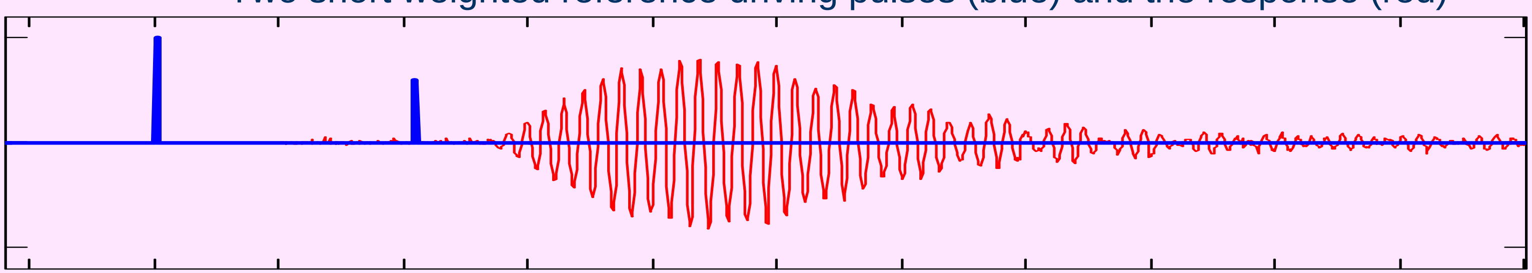
Find a weighted series of N reference pulses that generates a much shorter response

Example:

One short reference driving pulse (blue) and the response (red)



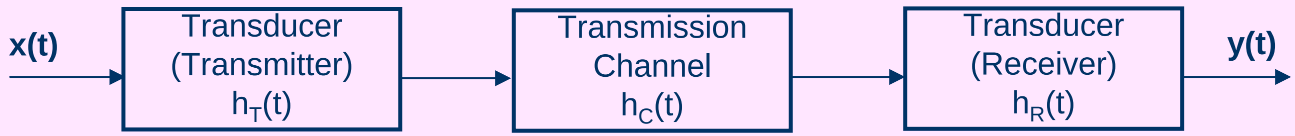
Two short weighted reference driving pulses (blue) and the response (red)



Brief summary of last year's paper

"Transducer to Transducer Time Domain Signal Response Shaping in Ultrasonic Applications"

Block diagram:



x(t): Driving signal, y(t): System response to x(t) excitation

$h_T(t)$: Transmitter transducer impulse response $h_C(t)$: Transmission channel impulse response $h_R(t)$: Receiver transducer impulse response

In the discrete time domain:

Step 1: Determine the short reference driving pulse system response $y_{SRP}(n)$

Step 2: Choose a desired response $y_{MPR}(n)$ = Mobj(n)

Let $x_{MPL}(n) = a_0\, x_{SRP}(n) + a_1\, x_{SRP}(n-1) + a_2\, x_{SRP}(n-2) + \ldots\ldots$ a weighted series of N reference pulses

Step 3: Compute $x_{MPL}(n)$ as follows:

$$[a_0, a_1, a_2 \ldots a_{N-1}] = Rpo^T \; Rpp^{-1}$$

Rpo = SRP-OTR cross-correlation vector
Rpp = SRP auto-correlation matrix
k = 0 …. N – 1, l = 0 …. N – 1

$$Rpo_k = \frac{1}{max - min} \cdot \sum_{n=min}^{max} Mobj(n) \cdot p(n-k)$$

$$Rpp_{k,l} = \frac{1}{max - min} \cdot \sum_{n=min}^{max} p(n-k) \cdot p(n-l)$$

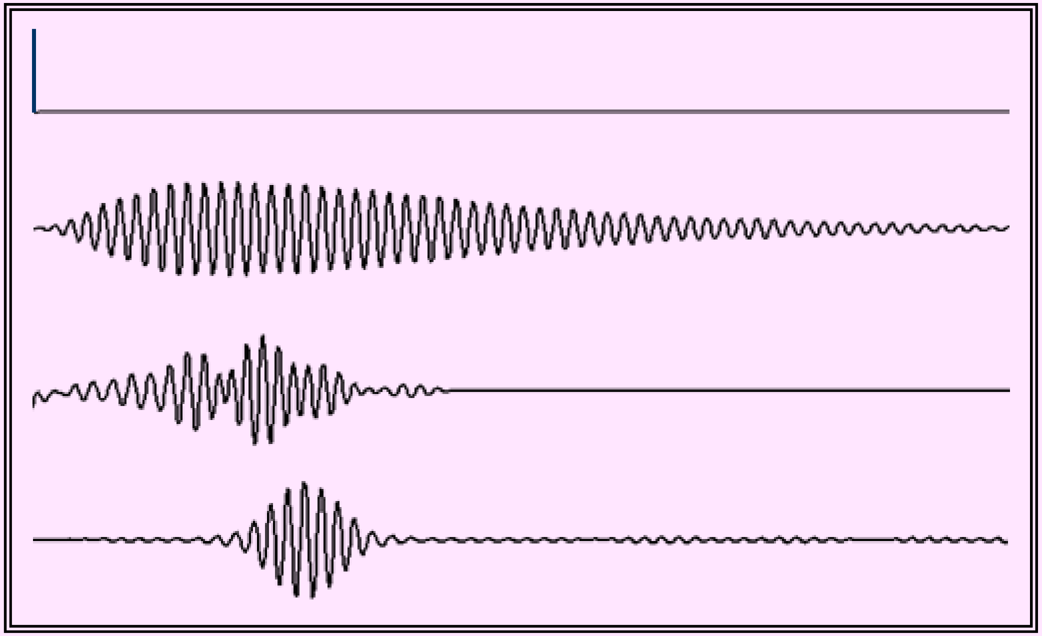
Transmitter “One-Symbol Driving Signal” Synthesis

Step 1: To obtain the “Transducer to Transducer Short-Reference Pulse Response “

Step 2: To determine the desired “Transducer to Transducer One-Symbol Response “

Step 3: To compute the “One Symbol Driving Signal” using the “Time Domain Signal Response Shaping” technique presented last year at the 2006 IEEE International Ultrasonics Symposium

Step 4: To confirm practically that the “Synthesized One Symbol Driving Signal” generates the desired response



Short-Reference Driving Pulse

Transducer to Transducer Short-Reference Pulse Response

Synthesized One-Symbol Driving Signal

Measured Transducer to Transducer Response from the Synthesized Driving Signal

2. Choosing the Right Modulation

What are the most serious challenges of typical indoor “Air-Channels“?

- The rapid decrease of the signal strength as a function of the distance
- The phase jitter due to air-turbulences or draughts current
- The reflections and echoes (i.e. multi-paths)

Other important parameters (constraints) to consider:

- Time Domain Response Shaping
- Transducers efficiency
- Global robustness
- Implementation

From the above enumeration of challenges and parameters,

BPSK (binary phase-shift keying) modulation

turns out to be the best possible choice.

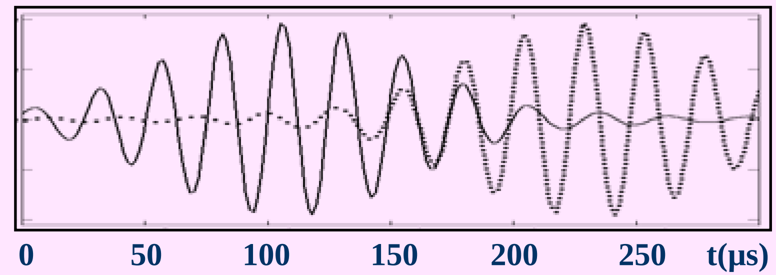
3. Data Modulated Driving Signal

Example: 8 kbps

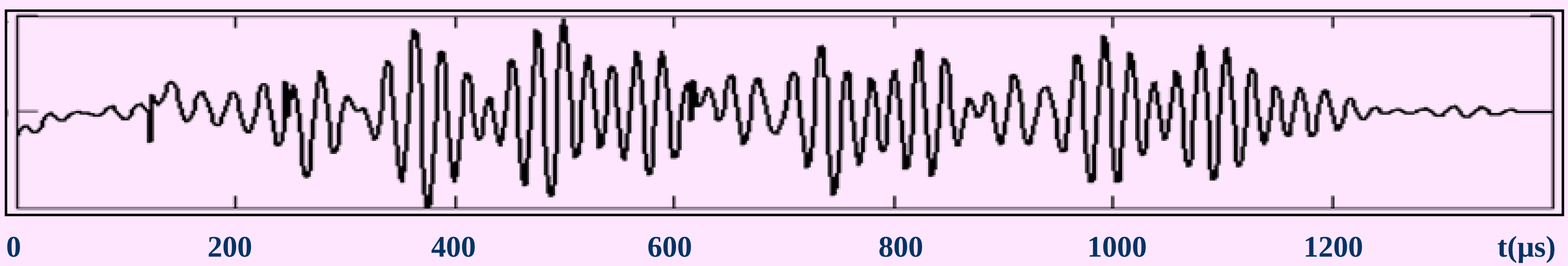
- ➔ transducer to transducer one-symbol response: ≈ 8 cycles
- ➔ one symbol corresponds to 5 cycles

PSK modulation is generated by adding or subtracting shifted replicas of the weighted reference pulses

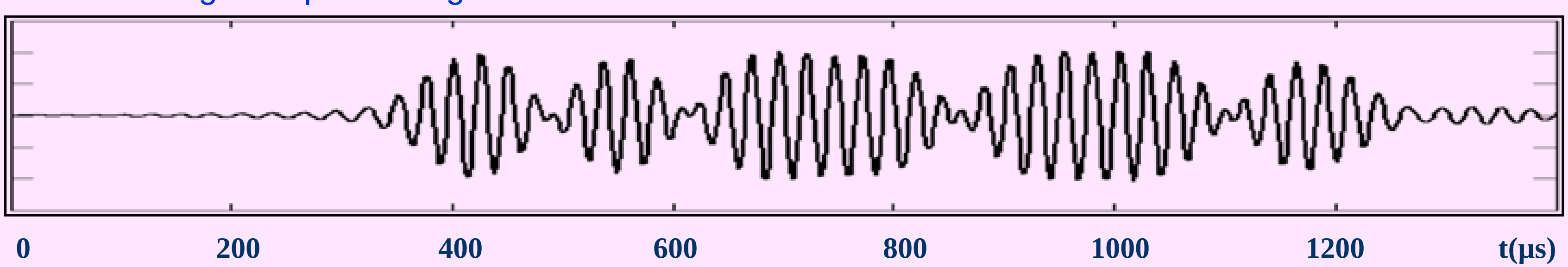
Two consecutive symbols with a spacing of exactly 5 cycles



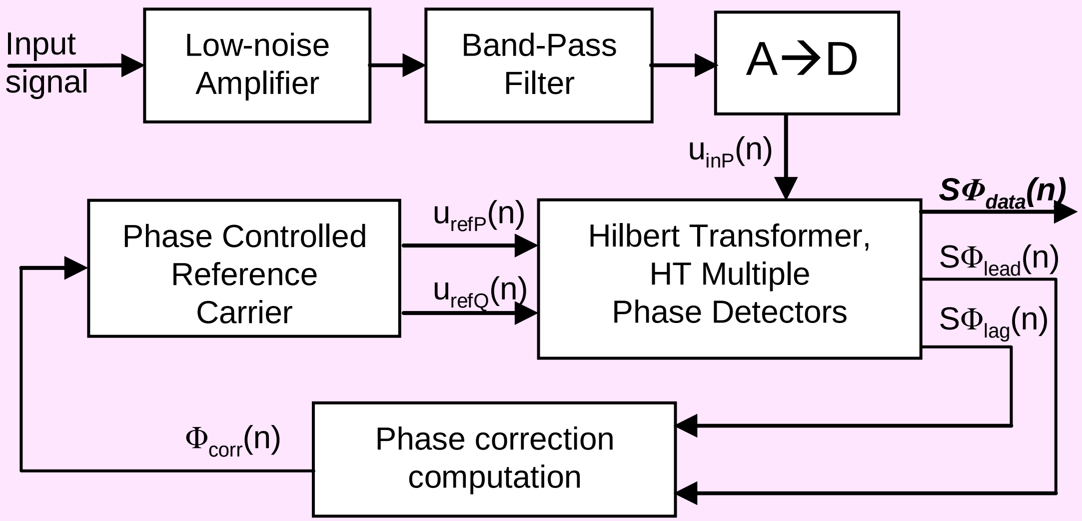
Driving signal representing 1 -1 1 1 -1 -1 1



Received signal representing 1 -1 1 1 -1 -1 1



4. Receiver Structure – It is based on a "Hilbert Transform Phase-Detector "



HT-PD advantages:

Quasi-Instantaneous Phase Estimation

Insensitivity to Amplitude Fluctuations

Particularly effective in Non-Stationary Conditions

HT-PD concept:

$u_{inP}(t) = U_{in}(t) \cdot \cos(2\pi \cdot fo \cdot t + \Phi_{in}(t))$: Band-limited input signal

$u_{refP}(t) = \cos(2\pi \cdot fo \cdot t + \Phi_{ref}(t))$: Reference carrier

$$\sin\left(\Phi_{in}(t) - \Phi_{ref}(t)\right) = \frac{u_{inP}(t) \cdot u_{refQ}(t) - u_{inQ}(t) \cdot u_{refP}(t)}{\sqrt{2} \cdot \sqrt{u_{inP}(t)^2 + u_{inQ}(t)^2}}$$

$$u_{inQ}(t) = H[u_{inP}(t)]$$

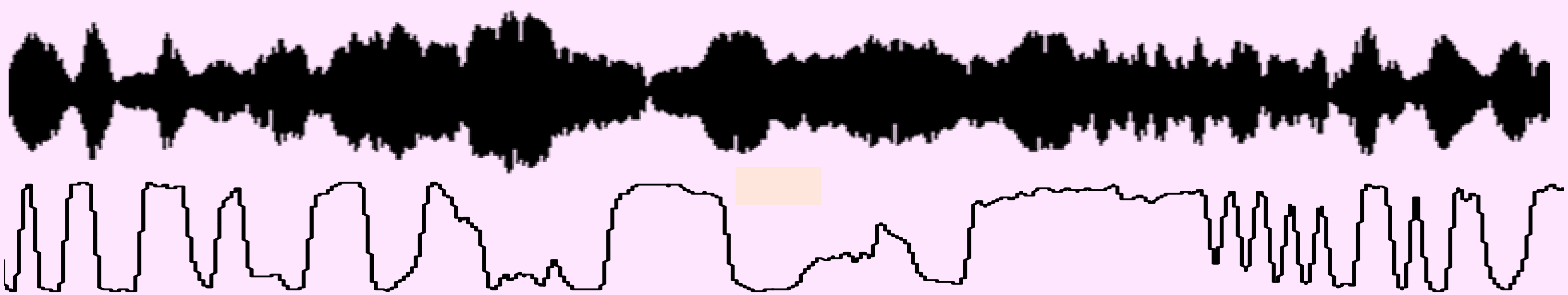
$$u_{refQ}(t) = H[u_{refP}(t)]$$

5a. Computer Simulations – Perfect synchronization (no phase-jitter, no noise)

No multi-path

Top: Receiver Input signal - Bottom: Hilbert Transform Phase-Detector Output

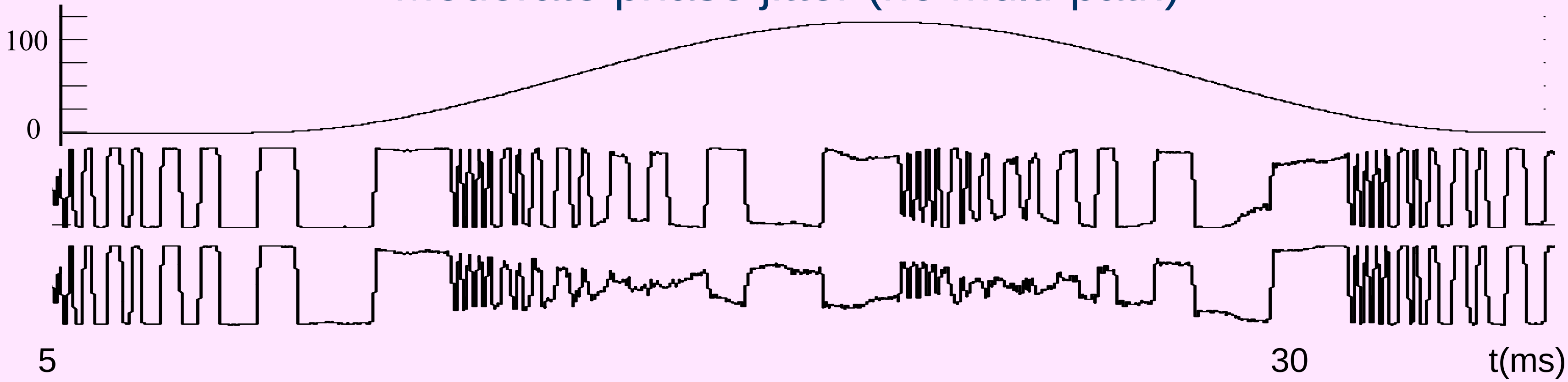
Multi-paths (three reflections)



Top: Input signal - Bottom: Hilbert Transform Phase-Detector Output

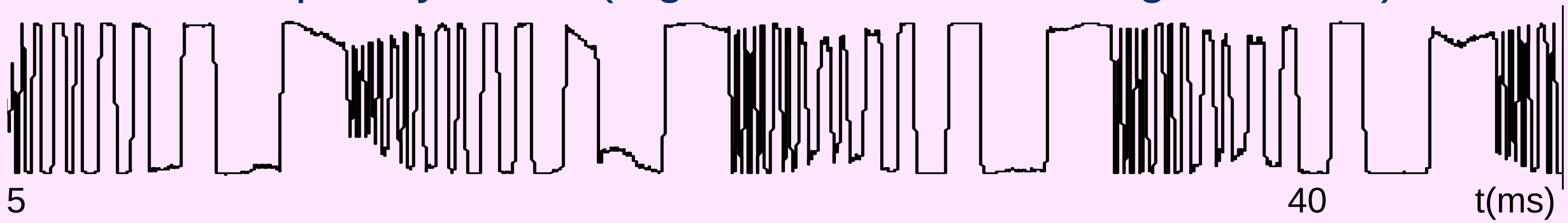
5b. Computer Simulations – Phase jitter and frequency-offset

Moderate phase jitter (no multi-path)



Top: Phase jitter [degrees] – Center: HT-PD with Synchro. – Bottom: HT-PD without Synchro.

Frequency-offset (e.g. 0.36 m/s from draught current)



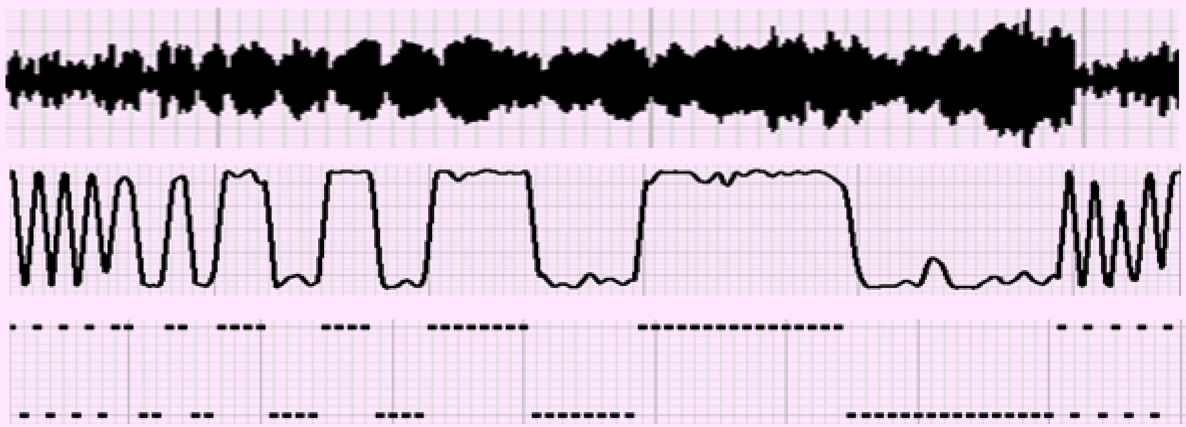
Comment: The global performances of the receiver quickly degrade with multi-path effects!

➔ Possible improvement: "Multi-Path Detector" …………………

6. Experimental Results

With low cost ceramic air transducers (400ST – 400SR)
Transmitter peak-to-peak voltage limited to 15 V
Measured averaged DC power: 30 mW (continuous mode)

8 kbs, 12 to 15 meters, air-channel without reflection

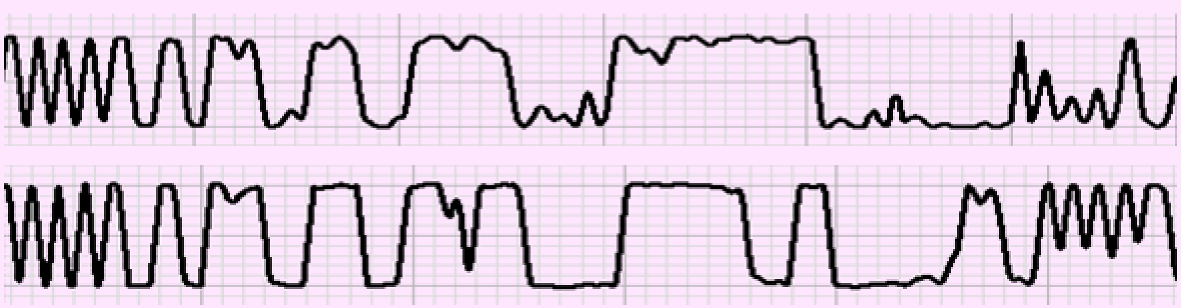


Input signal

HTDoutput

Recovered data

8 kbs, air-channel with reflections



Moderate reflections

Strong reflections

Problem:

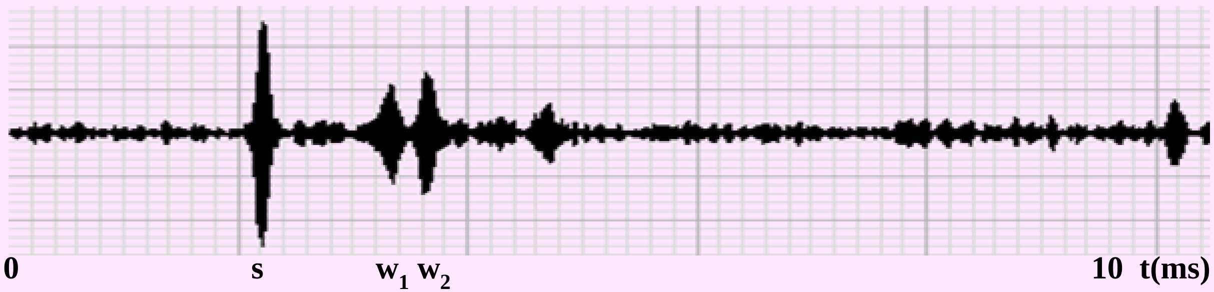
Strong reflections and echoes == > sharp increase of BER (bit-error-rate)

Solution:

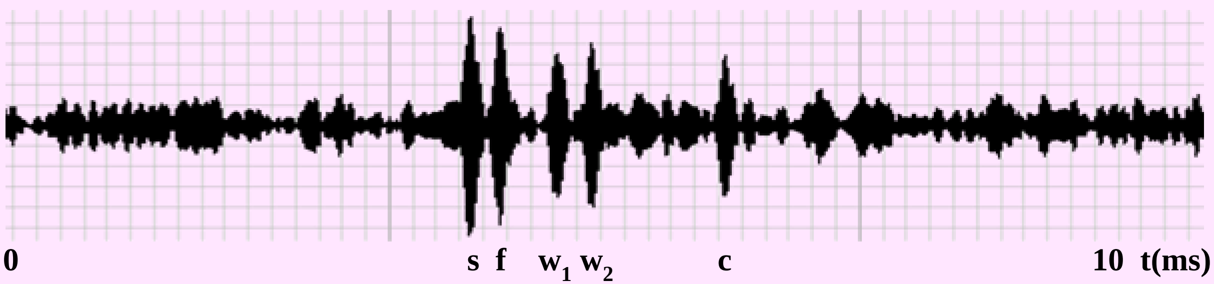
Channel profiling, i.e. air-channel one-symbol response measurement

== > Transmission format adaptation

Examples:



Several reflections of small amplitudes



Many strong reflections

In a hallway, distance: 16 m,

Both transducers at a height of 80 cm

Channel profiling - s: line-of-sight, f: floor, w1 - w2: walls, c: ceiling

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Adaptation of the transmission format -- bit position dependant power

Packets of 100 bits or less can greatly benefit from "bit-position power dependant"

Effective in case of
- strong reflections with arrival times larger than 20-30 bits
- numerous reflections of small amplitudes.

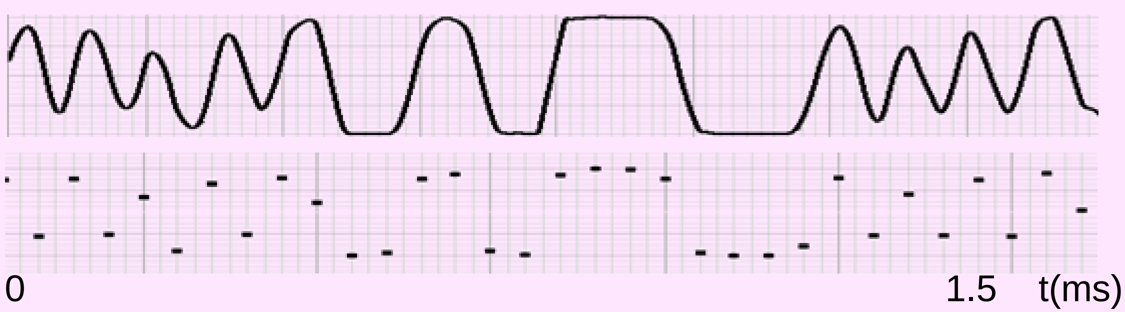
Data detection example (distance of 12 m):

Constant power (Pref→ 100%)

Linearly increased power (6% Pref → 100% Pref)

➔ Average power reduced

Final Challenge: Short Bursts at 20 kbs.



Results of transmitting short bursts of 32 bits at a distance of 10 meters.

The bandwidth of the transducers drastically limits the distance and the length of the burst

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7. Conclusions

Transfer of 128-bit data packets in 15 ms over distances of 10-12 meters with direct line-of-sight were achieved without error in air-channels with limited reflections.

“Hilbert Transform” receiver structure is very effective in typical "air-channels"

Channel profiling ➔ adaptation of the packet format to reduce the reflections effects (e.g. short data packets with bit-position dependant power)

Time domain response shaping ➔ Bandwidth widening achieved by signal processing
➔ No matching networks required

Application examples: **Untraceable indoor communication networks**

Highly secure pre-authentification

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Any Question ?

Comment ?