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

Jean-Paul Sandoz
Electrical Engineering Department
HE-ARC / HES-SO
Le Locle, Switzerland
e-mail: jean-paul.sandoz@he-arc.ch

Abstract— **This paper presents the results of a new solution to air-data transmission for medium distances (10–15meters) at rates in the order of 10 kbps. The key feature of this work is the use of low-cost narrow-band 40 kHz transducers along with a specially shaped driving signal. 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; thus achieving useful rates at medium range. In addition, a prior air-channel one-symbol response measurement (i.e. aerial channel profiling) can be used to adapt the packet format in order to reduce the reflections effect. Practical tests involving short data packets with bit-position dependant power have given encouraging results. Moreover, contrary to the classical bandwidth widening techniques which rely upon matching networks (i.e. capacitors - inductors), this new solution has the advantage of being exclusively signal processing based.**

Keywords: Ultrasonic Air-Data Transmission; Medium Distances; Shaped Driving Signal, Low-Cost Solution

I. INTRODUCTION

The increasing need for medium distance (10-15 meters), highly protected data transmission is generating a growing interest for air-data ultrasonic transmission [1, 2, 3 and 4]. This is due to the fact that electromagnetic transmissions are not secure enough or too easily traced while light waves are often impractical [5, 6, 7]. However, to date, no report or products have been identified for rates much above 300 bps at these ranges [8, 9]. A recent work [10] has demonstrated that from the knowledge of the transducer to transducer time domain pulse response, a driving signal can be computed in order to generate a predefined response of only a few cycles without overly reducing the transducers efficiency. This result turns out to be particularly useful with low-cost narrow-band 40 kHz ultrasonic transducers, making them usable for data transmission at rates up to 8-12 kbps at medium distance. Additionally, the unique indoor ultrasonic channel characteristics favour the use of burst type transmission with possible bit-position dependant power or burst length dynamic adaptation based on periodic channel profiling.

This paper is organized as follows: In section 2, the conceptual analysis is presented. In the next section, computer simulations are illustrated. Experimental results and challenges are discussed in section 4. Section 5 summarizes the advantages of this design and suggests potential developments. It also points out application domains that can benefit from this innovative solution.

II. CONCEPTUAL ANALYSIS

From communication theory, we know that several modulation schemes can be considered. However, in order to keep the transducers efficiency high enough, the specially formatted driving signal produces a time domain response at exactly the transducers natural frequency. Thus, modulations of the Frequency Shift Keying family cannot be easily implemented. Conversely, ON-OFF Keying or Phase Shift Keying (PSK) can both be used without difficulties. A careful analysis of "aerial ultrasonic channels" shows that reflections are often present. Moreover, the severe attenuation of air-channel definitely favours the very last enumerated type of modulation. This led to the development of a PSK based prototype system using a pair of narrow-band (800 Hz) low-cost 40 kHz transducers.

A. *Transmitter Driving Signal Selection*

The previous practical experiments [10] show that 400 to 500 weighted pulses of 1600 ns are necessary to synthesize the desired response. On Fig. 1 we present the "Transducer-to-Transducer Unit Pulse Response" $tt_{upr}(t)$, the desired response $tt_{desired}(t)$, the synthesized response $tt_{synthe}(t)$ and the computed driving signal $x_{drive}(t)$ made up of 400 coefficients.

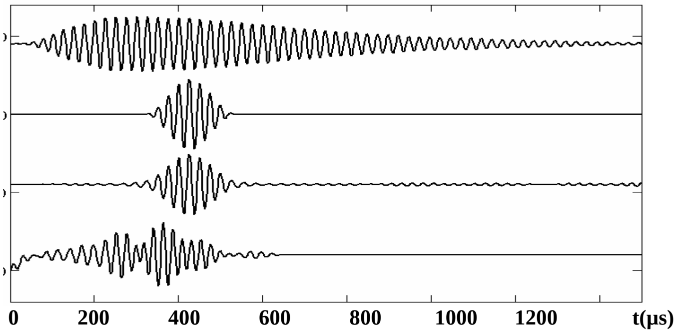

Figure 1. Top to bottom: $tt_{upr}(t)$ - $tt_{desired}(t)$ - $tt_{synthe}(t)$ - $x_{drive}(t)$

From the synthesized signal, we chose to transmit binary data at 8 kbps. This implied the duration of the transducer to transducer one-bit response to be of around 8 cycles with the duration a one-bit corresponding to exactly 5 cycles (Fig. 2).

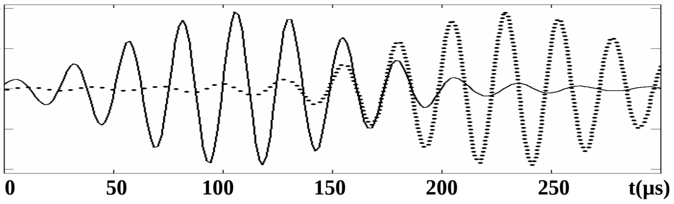

Figure 2. Two consecutive $tt_{synthe}(t)$ with a spacing of exactly 5 cycles

Subsequently, the PSK modulation is generated by adding or subtracting shifted replicas of the weighted pulses. This is illustrated in Fig. 3 whereas the "synthetically constructed" received signal is presented in Figs. 4 and 5.

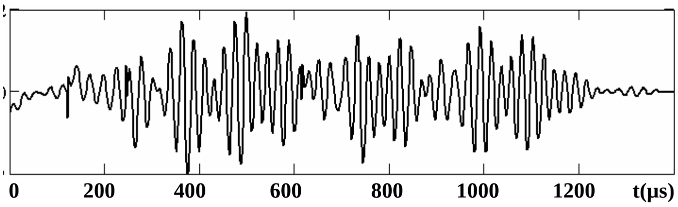

Figure 3. Driving signal representing 1 -1 1 1 -1 -1 1

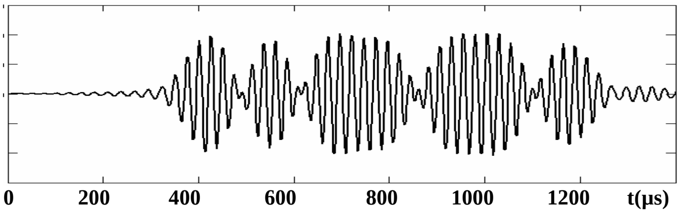

Figure 4. Reconstructed received signal representing 1 -1 1 1 -1 -1 1

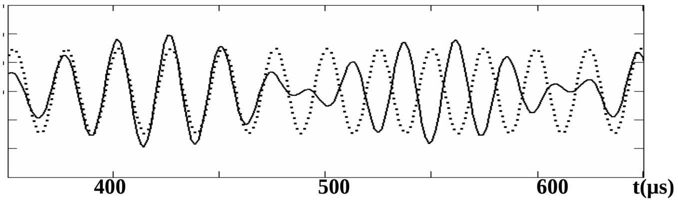

Figure 5. —— Reconstructed received signal representing 1 -1

···· Receiver reference carrier

B. *Receiver Structure*

In this paper, we will only consider indoor air-data transmission taking place in large reception lobbies and long corridors where distances can easily exceed 10 meters. Moreover, they are prone to draught current, multiple reflections (multi-paths), fading due to moving people and severe attenuation (i.e. in the order of 1.3 dB per meter at room temperature). These will particularly affect the short-time amplitude and phase stability of the received signal. Furthermore, impulsive and quasi-periodic noise can also be present. For all these reasons, the receiver structure must be chosen with a specific emphasis placed upon robustness and ease to adapt itself to unfriendly environment. From the extensive field tests conducted, we realised data recovery with a new "Hilbert Transform" instantaneous phase detector structure [11] whose theoretical foundation is summarized in the next paragraph.

Let $u_{inP}(t)$, the band-limited input signal and $u_{refP}(t)$, the reference carrier expressed as follows:

$$u_{inP}(t) = U_{in}(t)\cdot\cos(2\pi\cdot fo\cdot t + \Phi_{in}(t)) \tag{1}$$

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

where $U_{in}(t)$, $\Phi_{in}(t)$ and $\Phi_{ref}(t)$ are "slow" compared to fo (40 kHz). Then, from [11]:

$$\sin\left(\Phi_{in}(t) - \Phi_{ref}(t)\right) = \frac{u_{inP}(t)\cdot u_{refQ}(t) - u_{inQ}(t)\cdot u_{refP}(t)}{\sqrt{2}\cdot\sqrt{u_{inP}(t)^2 + u_{inQ}(t)^2}} \tag{3}$$

Note that $u_{inQ}(t)$ and $u_{refQ}(t)$ are the "Hilbert Transformation" of $u_{inP}(t)$ and $u_{refP}(t)$ respectively.

The two most important advantages of this phase detector are the insensitivity to amplitude fluctuations and its quasi-instantaneousness to give the phase estimation.

Since the carrier frequency is known with enough accuracy, the phase reference can be continuously evaluated and corrected by means of the well known "Lead-lag" scheme. Thus, there is no synchronization time required; therefore, signals transmitted in short bursts can also be demodulated. The complete receiver structure is presented in Fig. 6.

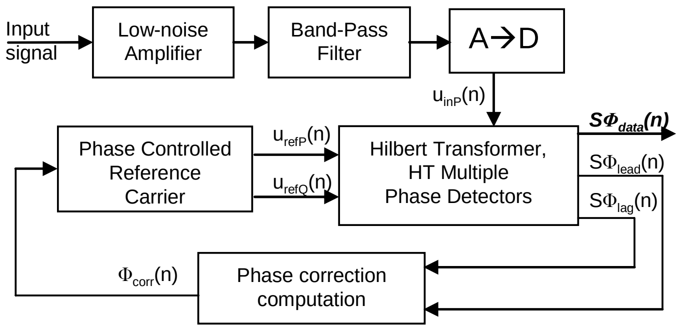

Figure 6. Complete receiver structure

Succinct description of the blocs:

Low-noise amplifier: 2-3 nV/√Hz to give best SNR

Band-pass filter: Centered at 40 kHz, bandwidth: 20 kHz

A→D: Analog-to-digital converter, sampling freq.= 625 kHz

Phase controlled reference carrier: Centered at around 40 kHz

HT Multiple PD: $S\Phi_{data}(n) = \sin(\Phi_{inP}(n) - \Phi_{refP}(n))$
$S\Phi_{lead}(n) = \sin(\Phi_{inP}(n) - \Phi_{refP}(n) + \Delta)$
$S\Phi_{lag}(n) = \sin(\Phi_{inP}(n) - \Phi_{refP}(n) - \Delta)$

where $\Delta \rightarrow 3\pi/8$

Phase correction computation:

$$\mathrm{Error}(n) = \sum_{k=n-d}^{n} \left[\left|S\Phi_{lead}(k)\right| - \left|S\Phi_{lag}(k)\right|\right] \tag{4}$$

$$\Phi_{corr}(n) = \alpha\cdot\sum_{m=0}^{n} \mathrm{Error}(m) \tag{5}$$

where d is the running averager length and α is the loop gain.

At the present time, no optimization has been done on this structure and we don't pretend that it is the best possible one. However, it performed extremely well during the large series of practical tests, exhibiting more robustness than the conventional coherent detector (CoD). Some illustrations and comparisons are given in the next section.

III. COMPUTER SIMULATIONS

A. *Perfect synchronization (no phase-jitter, no noise)*

Fig. 7 shows the "no multi-path" situation; as expected, the "Hilbert Transform" based detector (HTD) is not affected by the input signal envelop modulation.

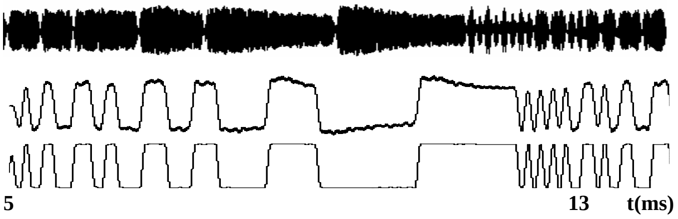

Figure 7. Top to bottom: Input signal, CoD and HTD

Fig. 8 shows the effects of three reflections with the following amplitude percentages relative to the line-of-sights and delays:

1st: 60% - 1.2 ms, 2nd: 40% - 1.6 ms and 3rd: 30% - 2.5 ms.

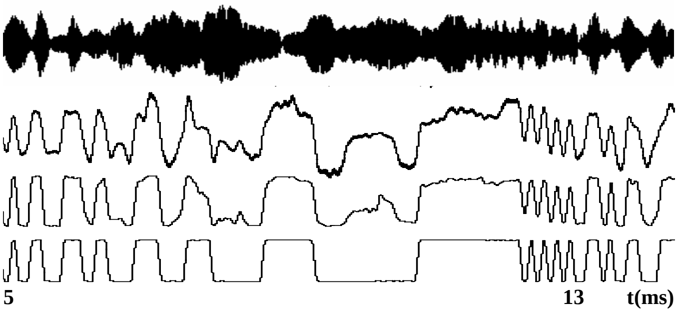

Figure 8. Top to bottom: Input signal, CoD, HTD and reference

B. *Synchronization from HTD, moderate phase jitter*

When the ultrasonic channel has turbulences (draught of air), rapid phase deviations can occur. Fig. 9 shows the effectiveness of the HTD based synchronization (SYNC). It is important to realize that the tracking ability of the loop quickly degrades as soon as multi-path effects take place.

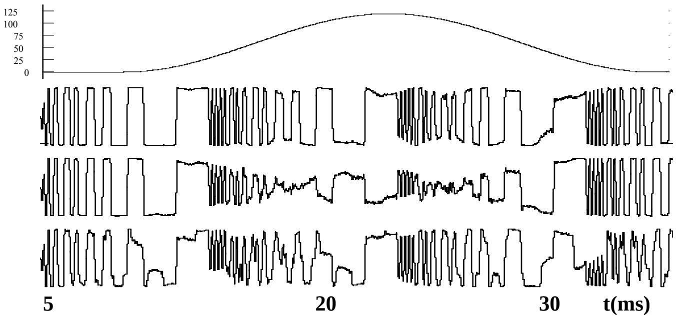

Fig. 9. Top → bottom: Phase jitter [°] , SYN, no SYNC, SYNC with one reflection (50% - 1.2 ms)

C. *Frequency-offset*

In areas where relatively strong draughts current are present, it will produce frequency-offsets in the order of 40 Hz (i.e. 0.36 m/s). Fig. 10 shows such a situation. In order to effectively deal with such cases, a frequency offset detector will have to be added to the receiver structure.

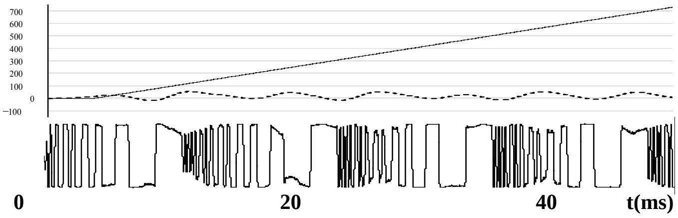

Fig. 10. Top: Phase deviation [°]; dotted line: tracking-error bottom: HTD

IV. EXPERIMENTAL RESULTS

Low cost ceramic air transducers (400ST – 400SR) were used for these experiments. The arbitrary waveform generator (ETC M631) was directly connected to the transmitting transducer; with a peak-to-peak voltage limited to 15 V. The measured averaged DC power was in the order of 30 mW (continuous mode).

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

Fig. 11 shows an example of an 8kbs data transmission at distances of 12 to 15 meters. Repeated experiments confirmed that data can be transmitted without error at these distances in air-channel without or with reflections of small amplitudes.

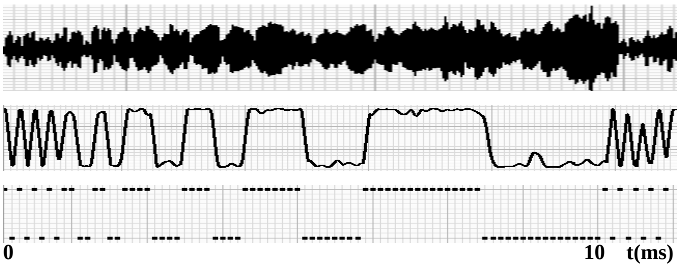

Fig. 11. Top: Input signal (filtered), Center: HTD, Bottom: recovered Data

B. *8 kbs, air-channel with reflections*

In these two examples (Fig. 12), a burst of 90 bits was transmitted in air-channels with reflections.

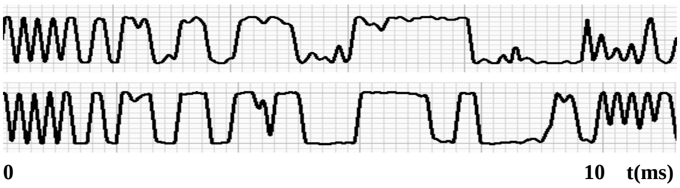

Fig. 12. Top: Moderate reflections, bottom: strong reflections

The obvious conclusion drawn from the many experiments done throughout this project is that: "*When the received signal is the sum of the direct signal (line-of-sight) and of reflections, the degradation grows rapidly with the number of strong reflections*". Consequently, a prior air-channel one-symbol (i.e. one-bit) response measurement (i.e. channel profiling) can be used to adapt the transmission format in order to neutralize these negative effects.

C. Channel Profiling

Fig. 13 shows "one-symbol" responses to three common air-channels:

1) Several reflections of small amplitudes
2) One strong reflection (750 µs → 6 symbols)
3) Many strong reflections (in a corridor, distance: 16 m, both transducers at a height of 80 cm)

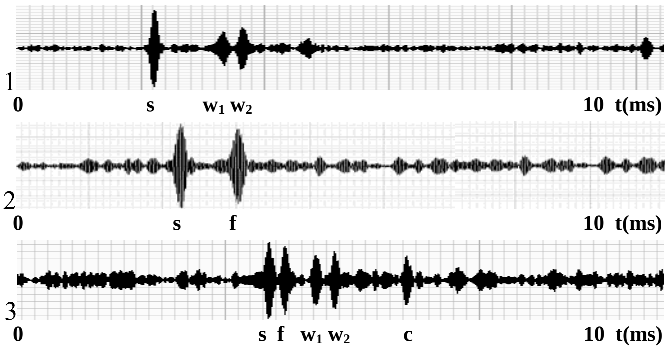

Fig. 13. Channel profiling (s: line-of-sight, f: floor, w_1 - w_2: walls, c: ceiling)

D. Bit Position Dependant Power

Packets of 100 bits or less can greatly benefit from "bit-position power dependant" strategy when the channel reflections are strong and their arrival times are larger than 20 to 30 bits (Fig. 14). It will also be effective when there are numerous reflections of small amplitudes. Fig. 15 shows such an example at a distance of 12 m.

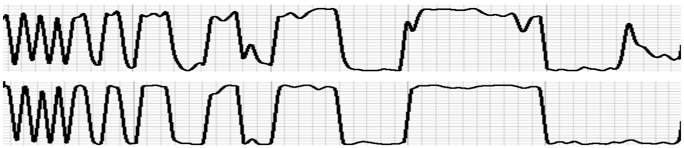

Fig. 14 Top: Data detection with constant power (Pref→ 100%)
Bottom: linearly increased power (6% Pref → 100% Pref)

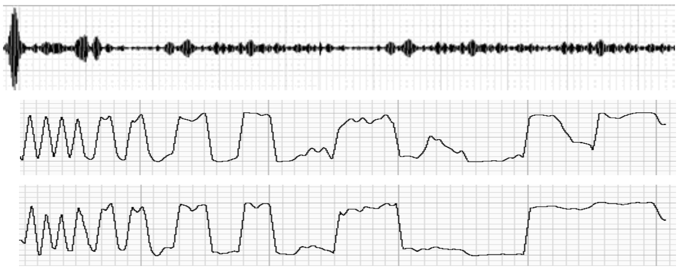

Fig. 14. Top: Channel profiling, Center: Data detection with constant power
Bottom: Data detection with linearly increased power (6% → 100%)

E. Short Bursts at 20 kbs

Finally, Fig. 15 shows the results of transmitting short bursts of 32 bits at a distance of 10 meters. In this case, the bandwidth of the transducers drastically limits the distance and the length of the burst.

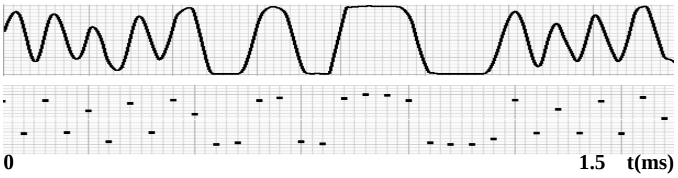

Fig. 15. The final challenge: 20 kbs!

V. 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; thus achieving useful rates at medium range. Moreover, a "Hilbert Transform" base receiver structure has shown its robustness for data detection as well as carrier synchronization with large phase-jitter. In addition, a prior air-channel one-symbol response measurement (i.e. aerial channel profiling) can be used to adapt the packet format in order to reduce the reflections effect. Practical tests involving short data packets with bit-position dependant power have given encouraging results and will be further developed. Finally, contrary to the classical bandwidth widening techniques which rely upon matching networks (i.e. capacitors - inductors), this new solution has the advantage of being exclusively signal processing based. Moreover, its effectiveness should boost the development of untraceable communication networks and other related applications.

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