Indoor Ultrasonic Transfer Function for Moving Objects

Daniel F. Albuquerque, José M. N. Vieira, Sérgio I. Lopes, Carlos A. C. Bastos, Paulo J. S. G. Ferreira
Signal Processing Lab – IEETA/DETI – University of Aveiro
3810-193 Aveiro, Portugal
{dfa, jnvieira, sil, cbastos, pjf}@ua.pt

***Abstract*—In this paper we present the Indoor Ultrasonic Transfer Function, IUTF, which models the ultrasonic acoustics of a given room for signal propagation between moving objects. The IUTF takes into account the distance between objects, the multiple reflections on the walls, the objects speed and the attenuation due to propagation and reflections. The proposed IUTF can also be used to model the propagation channel for ultrasonic data communication using single or multiple carriers between moving emitter/receiver. Therefore, this transfer function will be essential to design modulation schemes for indoor environments.**

***Index Terms*—Room acoustics, Acoustic propagation, Transfer function, Ultrasonic propagation, Doppler effect.**

I. INTRODUCTION

Indoor ultrasonic acoustic propagation presents similar problems to those experienced in electromagnetic waves propagation, such as multiple reflections, Doppler effect and propagation attenuation [1], [2]. Due to that, to properly design ultrasonic communication or location systems, a good model for the ultrasonic channel is needed.

Commercially available acoustic simulators, like ODEON [3], are very expensive and since they are not open source, changes are not possible. However, there are examples of freely available simulators [4], [5], [1] but none of them take into account the Doppler effect (very important in data communication [6]). Moreover, the Doppler effect has a stronger impact on ultrasonic communications than in radio frequency communications due to the lower speed of sound. For example, a person traveling at 1 $\mathrm{m/s}$ produces to a 40 KHz carrier a maximum Doppler shift [6] of 118 Hz. For radio communications at 1 GHz, to have an equivalent Doppler shift, the person needs to travel at more than 35000 $\mathrm{m/s}$ (126000 $\mathrm{Km/h}$). Nevertheless, in [2] is presented a simulator for Doppler effect in sound, although, this simulator applies the Doppler effect directly to the signal, it will not be useful for ultrasonic signals due to the need of a much higher sampling rate.

In this paper we present a mathematical model for the Indoor Ultrasonic Transfer Function, IUTF. The proposed method reduces the sampling frequency before apply the indoor environment effect to the signal, which optimizes the computation time.

This paper is organized as follows: in the next section is presented a brief description of a previously developed Room Acoustic Simulator. In section III we will present the Indoor Ultrasonic Transfer Function. At the end it will be presented some simulation results and the conclusion.

II. ROOM ACOUSTIC SIMULATOR

The simulator implemented by the authors and presented in [7], is an acoustic simulator that assumes specular reflections and aimed to simulate ultrasonic signals propagation. This simulator can compute all the *virtual sources*' position produced by acoustic reflections of the original sound source in the room walls. Moreover, this simulator can compute the time delay and attenuation for each multiple reflected signal as a function of the signal frequency, room temperature, air pressure and humidity. The proposed simulator was used to model a real indoor environment and it closely matches the experimental observations.

A. Multiple Reflections Model

To compute the *virtual sources* position it was used a hybrid method based on the image source method with ray tracing validation [8]. This method considers all the wave reflections as specular, which is a good approximation to the way that the sound waves propagate in closed spaces, when the wavelength is much smaller than the obstacles.

B. Sound Propagation Model

When an acoustic signal propagates in the air it is attenuated by dispersion, due to the distance to the source, and by the atmospheric absorption. Both attenuations are referenced to a distance d_r. From [7], the total attenuation Λ of a signal sent at $t = 0$ and received at τ_0 is given by

$$\Lambda(\tau_0) = \frac{d_r}{c\tau_0} 10^{\frac{\alpha(c\tau_0 - d_r)}{20}} \tag{1}$$

where c is the sound speed in $\mathrm{m/s}$ and α is the attenuation by the atmosphere absorption in $\mathrm{dB/m}$ (around 1.2 $\mathrm{dB/m}$ for 40 KHz in default atmospheric conditions [7]).

III. INDOOR ULTRASONIC TRANSFER FUNCTION

In section III-A it will be defined a mathematical representation for band-pass signals that will be usefull for the system analysis and simulation. Therefore in III-B, it will be introduced a simplified version of the IUTF that includes the signal delay and attenuation due to the ultrasonic acoustic propagation proprieties. After that, in III-C it will be included the multipath effect due to the indoor reflections and in

III-D the Doppler effect due to the source/receiver movement. Finally, all this effects will be combined into a single IUTF.

A. Signal Representation

Assuming a sinusoidal signal based, a transmitted signal can be represented as [6]:

$$x(t) = a(t) \cos\left[(\theta(t) + 2\pi f_c t\right] \tag{2}$$

where $a(t)$ is the signal envelope and $\theta(t)$ the phase. As all the information is represented by the envelope and phase [6], the signal $x(t)$ can be represented only by its complex envelope $s(t)$ (or sometimes called low-pass representation):

$$s(t) = a(t) e^{j\theta(t)} \tag{3}$$

In order to recover the band-pass signal $x(t)$ from $s(t)$, it is necessary to multiply it by the carrier and get its real value. This approach reduces the need of a high sampling rate to represent the same signal, which is extremely important to reduce the simulation time. For example, to represent a band-pass signal with 1 KHz of bandwidth and a carrier of 40 KHz it would be necessary a sampling frequency higher than 82 KHz. Otherwise, its complex envelope representation only needs a rate of 1000 complex samples per second.

B. Signal Delay

Due to the speed of sound, the sent signal takes some time τ_0 to travel from the source to the receiver. Therefore, considering a distance $c\tau_0$ between the source and the receiver, the received signal $y(t)$ can be written as:

$$y(t) = x(t - \tau_0) \tag{4}$$

Similar to $x(t)$, $y(t)$ can also be represented by its complex envelope $r(t)$:

$$r(t) = s\left(t - \tau_0\right) e^{-j2\pi f_c \tau_0} \tag{5}$$

Combining equations (5) and (1), the received complex envelope signal $r(t)$ can be written as a function of the transmitted complex envelope signal $s(t)$ as

$$\begin{aligned} r(t) &= \Lambda(\tau_0)\ s\left(t - \tau_0\right)\ e^{-j2\pi f_c \tau_0} \\ r(t) &= \int_{-\infty}^{+\infty} s(t-\tau) h(\tau) d\tau = (s * h)(t) \end{aligned} \tag{6}$$

where $h(\tau)$ is the IUTF, and for a system without reflections and movement is given by:

$$h(\tau) = \Lambda(\tau_0)\ \delta(\tau - \tau_0)\ e^{-j2\pi f_c \tau_0} \tag{7}$$

$$\delta(\tau) = \begin{cases} 1, & \tau = 0 \\ 0, & \tau \neq 0. \end{cases} \tag{8}$$

C. Multiple Reflections Effect

When an acoustic signal propagates in an indoor environment it is reflected by surfaces, therefore, it will arrive to the receiver at different times and from different directions. As a result of this, each reflected signal arrives with a different delay. Generalizing to N reflected signals, the multiple reflections effect can be introduced into the IUTF:

$$h(\tau) = \sum_{n=0}^{N} \rho_n\ \Lambda(\tau_n)\ \delta(\tau - \tau_n)\ e^{-j2\pi f_c \tau_n} \tag{9}$$

where, ρ_n (≤ 1) is the attenuation factor due to the reflection coefficient of the walls. Note that, $n = 0$, represents the direct signal.

D. Doppler Effect

The Doppler effect is produced by the receiver and/or source movement. Moreover, the Doppler effect can be characterized by a compression or expansion of the acoustic signal, in the time domain, proportional to the source/receiver relative movement.

When the receiver moves, the distance between the source and the receiver changes over time, therefore, the travel time τ_0 will be different for each instant t. Introducing this effect in our model leads to

$$\begin{aligned} r(t) &= s\left(t - \tau_0(t)\right)\ \Lambda(\tau_0(t))\ e^{-j2\pi f_c \tau_0(t)} \\ r(t) &= \int_{-\infty}^{+\infty} s(t-\tau) h(\tau, t) d\tau = (s * h)(t) \end{aligned} \tag{10}$$

Moreover, for a system without reflections the IUTF is given by:

$$h(\tau, t) = \Lambda(\tau_0(t))\ \delta(\tau - \tau_0(t))\ e^{-j2\pi f_c \tau_0(t)}. \tag{11}$$

When the receiver moves in a rectilinear path with constant speed (zero acceleration) as shown in Figure 1, the distance from the source to the receiver can be written as:

$$\begin{aligned} d(t) &= d_h \sin\phi(t) + d_w \cos\phi(t) - vt\cos\phi(t) \\ d(t) &= d_0 \cos\left[\phi(t) - \phi_0\right] - vt\cos\phi(t) \end{aligned} \tag{12}$$

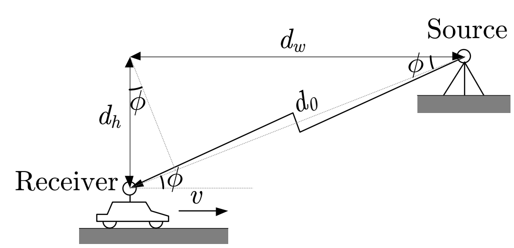

Fig. 1. Movement in any direction.

Which means that the delay τ_0 between the source and the receiver will be a function of t:

$$\tau_0(t) = \frac{d(t)}{c} = \tau_0 \cos\left[\phi(t) - \phi_0\right] - \frac{v}{c} t \cos\phi(t) \tag{13}$$

where $\phi(t)$ is the angle between the receiver movement direction and the line that passes throw the source and the receiver at time t, as it is shown in Figure 1.

The IUTF becomes:

$$h(\tau, t) = \Lambda[\tau_0(t)] \; \delta[\tau - \tau_0(t)] \times e^{-j2\pi f_c \tau_0 \cos[\phi(t)-\phi_0]} \; e^{j2\pi f_D t \cos\phi(t)} \quad (14)$$

From (14) it can be seen that the signal's frequency will be shifted by $f_D \cos\phi(t)$, where f_D can be seen as the maximum Doppler frequency shift (well know in telecommunication systems [6]):

$$f_D = \frac{v}{c} f_c. \quad (15)$$

E. Combining Multipath and Doppler Effects

Combining the equations (9) and (11), it is possible to obtain a single IUTF for any indoor enviroment:

$$h(\tau, t) = \sum_{n=0}^{N} \rho_n \; \Lambda[\tau_n(t)] \; \delta[\tau - \tau_n(t)] \; e^{-j2\pi f_c \tau_n(t)} \quad (16)$$

with,

$$\tau_n(t) = \frac{d_n(t)}{c} \quad (17)$$

where $d_n(t)$ is the distance between the receiver and the nth source at instant t.

IV. Simulation Results

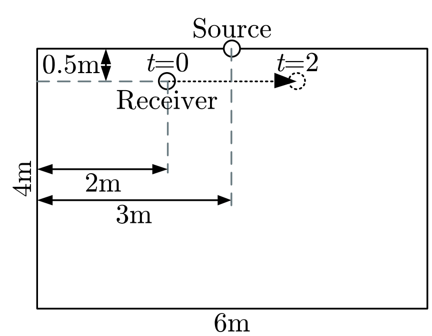

Fig. 2. Static source and receiver moving at 1 m/s in a 3 m high virtual room (Source and Receiver placed at 1 meter from the floor).

Using the simulation environment shown in Figure 2 and the room acoustic simulator described in section II it is possible to obtain all the virtual sources that produce the received reflections for each receiver position. Moreover, we considered a reflection coefficient of 1 (the reflected wave has the same amplitude of the incident wave in the wall) which means that ρ_n in (16) will be equal to 1. The reference distance d_r, was set to 1 m and an omnidirectional source was considered.

A. Single Sinusoid

Firstly it is presented the effect into the sinusoid without reflections from the room. Figure 3 shows that the sinusoid's frequency changes considerable. Moreover, from Table I can be seen that for the initial position ($t = 0$) the frequency shift will be 104 Hz, zero for $\phi(t) = \pi/2$ and -104 Hz at the end position. Therefore, the sinusoid will change from 40104 to 39896 Hz. According to this results if no scheme is adopted in the receiver to support these frequency changes, it will be difficult to demodulate the sent information using a 40 KHz carrier over this channel [6].

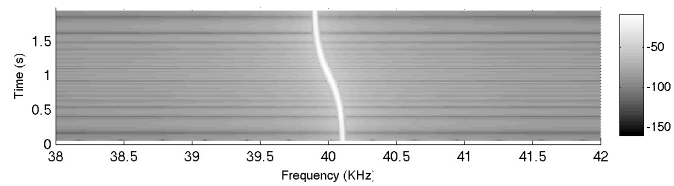

Fig. 3. Doppler effect into a 40 KHz sinusoid for a 1 m/s receiver speed.

t (s)	0.00	0.42	0.73	1.00	1.27	1.58	2.00
y (cm)	200	242	273	300	327	358	400
d (cm)	112	77	57	50	57	77	112
ϕ (°)	26.6	40.8	61.6	90	118.4	139.2	153.4
freq. shift	104	88	55	0	-55	-88	-104

TABLE I
DOPPLER EFFECT INTO A 40 KHz SINUSOID FOR A 1 m/s RECEIVER SPEED AT DIFFERENT POSITIONS.

When multiple reflections are introduced, the resultant signal will be a mixture of different sinusoids with different frequencies due to reflected waves arriving to the receiver with different ϕ (Figure 1). At 1 m/s this mixture can have sinusoids with frequencies shifts of the maximum Doppler frequency shift (from 39884 to 40116 Hz, equation (15)), this effect can be seen in Figure 4 for the same room example.

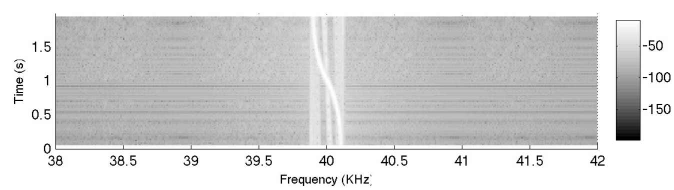

Fig. 4. Multiple reflections and Doppler effect into a 40 KHz sinusoid for a 1 m/s receiver speed.

B. Multiple Sinusoids

By using multi-carrier modulation such as Orthogonal Frequency-Division Multiplexing, OFDM, the Doppler effect not only changes the carrier frequency but will also create interference between adjacent carriers. Figure 5 presents 13 carriers of a multi-carrier system operating from 38400 to 40600. Therefore the minimum carrier distance is 100 Hz. From Table I can be seen that this correspond to the maximum

Doppler shift. As a result of this, the carrier 1 for $t = 0$ will be demodulated as carrier 2 and for $t = 2$ as carrier 0.

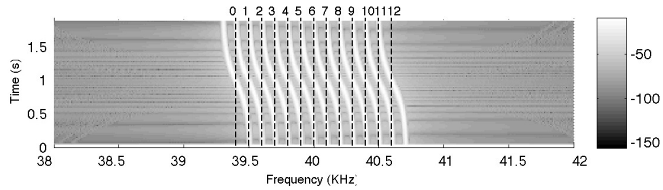

Fig. 5. Doppler effect into 13 carriers of a multi-carrier system operating from 38400 to 40600 for a 1 $\mathrm{m/s}$ receiver speed.

Furthermore, a received signal is a mixture of different reflected waves that arrive into the receiver with different angles, due Doppler effect each reflected wave will have a different frequency shift, which will introduce inter-carrier distortion. Figure 6 presents the same 13 carriers, from there can be seen at light gray the inter-carrier distortion.

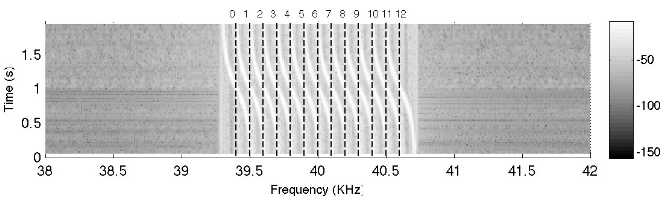

Fig. 6. Multiple reflections and Doppler effect into 13 carriers of a multi-carrier system operating from 38400 to 40600 for a 1 $\mathrm{m/s}$ receiver speed.

C. Modulated Signal

The IUTF can also be applied directly to modulated signals. In order to demonstrate that we can creat an example where random information modulated with quadrature phase-shift keying (QPSK) [6] with a symbol duration of 1 ms is used. In the simulator we used the same example of the single sinusoid with Doppler effect and multiple reflections. The received signal in frequency domain is presented in 7.

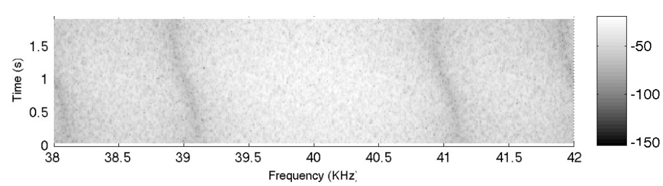

Fig. 7. Multiple reflections and Doppler effect into a communication signal modulated QPSK with a 40 KHz carrier for a 1 $\mathrm{m/s}$ receiver speed.

For communications over this conditions, it will be difficult to demodulate the received signal as can be seen in the modulation constellation of the received signal (Figure 8). Moreover, if the receiver uses a bandpass filter centered in the 40 KHz in order to reduce the noise [6], it will be important for filter to accommodate those frequency shift ranges, therefore, more noise will be received.

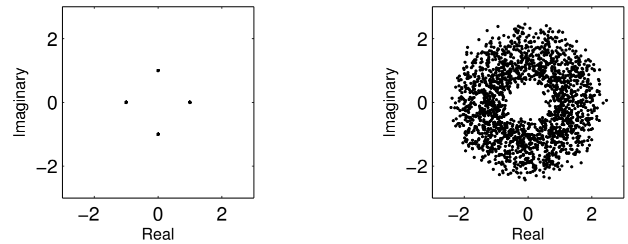

Fig. 8. Modulation constellation of the sent signal (left) and received signal (right).

V. CONCLUSION

From the results of the simulation, we can conclude that the presented Indoor Ultrasonic Transfer Function can be used as an approximation of the acoustic channel in ultrasonic propagation signals when the source and/or receiver have movement. For that purpose this transfer function includes the propagation delay, the attenuation due to dispersion and absorption, the Doppler effect and the multiple reflections effect that are present in most of the indoor environments. Therefore it can be used to design modulation schemes and reception strategies in order to reduce the impact of the channel in the received signal. As a result of this work, the actual version of the IUTF can be introduced in our simulator in order to increase the simulation accuracy for ultrasonic signals propagation. At the end, this modified version of the simulator could be useful to test the behavior of ultrasonic communication and ultrasonic location systems in closed spaces.

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This simulator is available at the URL:
http://www.ieeta.pt/locus/locusim/

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