Contributions of various transmission paths to speech privacy of open ceiling meeting rooms in open-plan offices

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Abstract

Installing open ceiling meeting rooms inside a large open-plan office provides a solution to increase speech privacy and to reduce speech disturbance in the office. The open ceiling meeting rooms have advantages of low cost construction and flexibility, but have lower speech privacy than that of enclosed rooms due to the open ceiling. Existing research shows that many factors should be taken into account to achieve good speech privacy in open-plan offices and improving only one of these factors may result in little improvement, so it is important to distinguish contributions of different acoustic transmission paths of open ceiling meeting rooms in open-plan offices. This paper proposes an impulse response separation method to quantify contributions of various acoustic paths of open ceiling rooms on speech privacy in open-plan offices. The method is verified with simulations based on the Odeon software and the experiments carried out in 3 different types of rooms. Finally, the proposed method is applied to the Fabpod, a semi enclosed meeting room located in a large indoor office at the Design Research Institute of the RMIT University, to obtain the contributions of different acoustic transmission paths to its speech privacy. The method proposed in this paper and the knowledge obtained are useful for architects to improve the acoustic performance of the next generation Fabpods which are now under design at RMIT University.

Keywords: speech privacy; open-plan office

1 Introduction

Since late 1960s, open-plan offices have been popular among design professionals [1]. Large open-plan offices have advantages of low cost construction and flexibility, but sometimes they lack speech privacy and result in speech disturbance when people are talking. Installing small closed meeting rooms inside open-plan offices provides a solution to the problem; however, the ceiling increases the cost of the meeting rooms due to the requirements of fire safety regulations and extra ventilation and lighting systems. Keeping the ceiling open or removing the ceiling of meeting rooms is an option; but the challenge is the low speech privacy due to sound propagating out through the open ceiling. There are several acoustic transmission paths through which sound radiates out from open ceiling meeting rooms into open-plan offices, and their relative contributions to speech privacy will be analyzed in this paper.

Speech privacy is related to the speech to noise ratio and represents the opposite of Speech Intelligibility (SI) to some extent [2]. In North America, Articulation Index (AI) and the Speech Intelligibility Index (SII) are widely used to represent the speech privacy while the Speech Transmission Index (STI) is used in Europe to represent speech privacy in open-plan offices [3]. STI is a physical quantity representing the transmission quality of speech with respect to intelligibility, and this paper uses it to evaluate the speech privacy of open ceiling meeting rooms in open-plan offices [4].

The relationship between room acoustic parameters and speech privacy of open-plan offices has been investigated by some researchers [5-7]. An international measurement standard was published in 2012, which uses single number quantities to indicate the general acoustic performance of open-plan offices [5]. The converted four single number quantities are the distraction distance, the spatial decay rate of speech, the A-weighted Sound Pressure Level (SPL) of speech at 4-m-distance and the average A-weighted background noise level, and can be determined by the spatial curves of A-weighted SPL of speech and STI in the office [6]. On the other hand, these single number quantities can be estimated by physical and acoustic parameters of rooms, which include the length, width, height of the room, the ceiling absorption, the screen height and apparent furnishing absorption [7].

To achieve good speech privacy performance, many room acoustic parameters should be considered at the same time and improving only one of these factors may result in little improvement if it is not the most critical one [3]. To identify the most critical factor, it is necessary to explore the influence of each parameter separately. Acoustical elements that can affect the acoustical environment in open-plan offices, such as windows, walls, ceilings and partial height screens, have been investigated experimentally [8]. But these experimental case studies lack quantitative analysis, which makes it hard to consider all important factors at the same time and compare the influence of different room acoustic parameters. An alternative way is to develop analytical models. A simple model of a single screen in an open-plan office with ceiling and floor reflections has been developed by using the image source technique [9]. A more complicated model took the effects of side and back panels of the common separating screen into account, and was used to investigate the sound propagation between two adjacent rectangular workstations in an open-plan office [10]. Some models even considered wall reflections and reverberation [11].

There are many acoustic transmission paths for open ceiling meeting rooms to radiate sound out into open-plan offices. The paths of reflecting from the ceiling and diffracting over the panel are relatively important while transmitting through the panel, reverberating in the room and reflecting by office equipment cannot be ignored either [11]. Based on the analytical models, the ceiling sound absorption, the panel height of the open-plan office and the office size were found to be the most important factors, while panel absorption, panel transmission loss, floor absorption, ceiling height and the details of ceiling mounted lighting could not be ignored though less important [2]. By optimizing all these room acoustic parameters simultaneously, good acoustic design can be obtained to meet the criterion for acceptable speech privacy.

The acoustic impulse responses of a room can provide most important acoustic information of the room [12]. For example, some important room acoustic parameters like reverberation time can be estimated from the room impulse responses [13]. Commercial room acoustic software such as Odeon and Dirac can be used to obtain a variety of parameters from the impulse responses [14, 15]. Bradley used the impulse responses to describe energy diffracted by the panels and reflected by the ceiling to compare their influence on speech privacy in actual rooms [3]. But these studies are limited to qualitative analysis and hardly provide direct solutions to acoustic design of open ceiling meeting rooms in open-plan offices.

This paper extends the existing research to quantitative analysis of room impulse responses in different frequency bands. An impulse response separation method is proposed, and it is verified with simulations based on the Odeon software and the experiments carried out in 3 different types of rooms. Finally, the proposed method is applied to the Fabpod, a semi enclosed meeting room located in a large indoor office at the Design Research Institute of the RMIT University, to obtain the relative contributions of different acoustic transmission paths to its speech privacy. This method and knowledge obtained can be used by architects to improve the acoustics performance of the next generation Fabpods which are now under design at RMIT University.

2 The Method

Open ceiling rooms in large offices can be treated as workstations in the acoustic design in open-plan offices. The layout and arrangement of the workstations are important in open-plan office design, while other factors cannot be ignored as well, such as sound absorption, height of screens, degree of workstation enclosure, and room dimensions [5]. The speech signal received in a closed room is the superposition of direct sound and reverberant sound. Reflections arrived within 50 ms after the direct sound are defined as early reflections, which are considered as useful for speech communication while those arrived later are defined as later reflections and are considered as harmful [11]. Thus, the contributions of direct sound and early reflections are considered first.

For positions outside an open ceiling meeting room in a large office, sound transmitting through panels is usually negligible compared with that transmitting through other paths because the transmission loss of the panels is usually more than 20 dB. Sound diffracting over the panels usually dominates the sound field outside the meeting room; however, if the absorption of ceiling is not large, sound reflecting from the ceiling might also become important. Sometimes, sound reflecting from the ground also plays an important role. Several acoustic transmission paths are shown in Fig. 1. Other paths such as reflecting from the ground or other walls inside the meeting room and then diffracting over the panel are less important, so they are not illustrated in the figure.

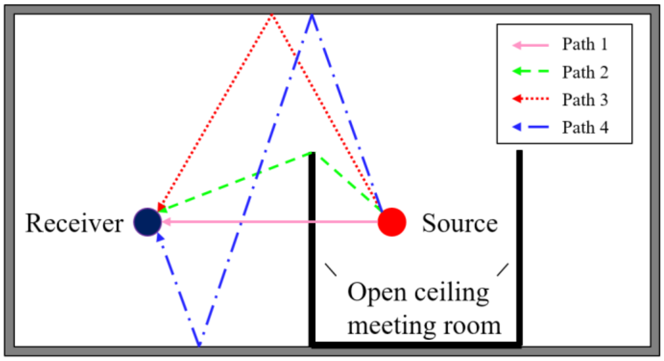


Figure 1 Typical acoustic paths for sound transmitting from inside to outside a meeting room, where Path 1 is that transmitting through the panel, Path 2 is that diffracting over the panel, Path 3 is that reflecting from the ceiling, and Path 4 is that reflecting from the ceiling and ground.

2.1 The theoretical method

The sound pressure level of sound transmitting through the direct path (without panel blocking) depends on the sound power of the sound source and the distance between the source and receiver [11]

$$L_{\mathrm{p,\,d}} = L_{\mathrm{W}} - 10\log_{10}\left(4\pi d^2\right), \tag{1}$$

where L_{W} is the sound power level of the sound source and d is the distance between the source and receiver. The sound diffracting over the panel can be obtained with the MacDonald solution [16, 17].

$$L_{\mathrm{p,\,diff}} = L_{\mathrm{p,\,d}} - IL, \tag{2}$$

where the insertion loss IL can be calculated with

$$IL = 20\log_{10}\left|\frac{\mathrm{e}^{\mathrm{i}(kR+\pi/4)}}{r}\sqrt{\frac{\pi R_1}{2k}}\left[\begin{array}{l}\dfrac{\mathrm{sgn}\left(\pi+\alpha-\phi\right)\mathrm{e}^{\mathrm{i}kR}}{\sqrt{k\left(R_1+R\right)}}Fr\left(\sqrt{\dfrac{2k}{\pi}\left(R_1-R\right)}\right)\\ +\dfrac{\mathrm{sgn}\left(\pi-\alpha-\phi\right)\mathrm{e}^{\mathrm{i}kR'}}{\sqrt{k\left(R_1+R'\right)}}Fr\left(\sqrt{\dfrac{2k}{\pi}\left(R_1-R'\right)}\right)\end{array}\right]^{-1}\right|, \tag{3}$$

where α and ϕ are the angle coordinates of source and receiver in cylindrical coordinates, k is the wave number, R and R' are the distance from the receiver to the source and mirror-image of the source, R_1 is the shortest distance from the source to the receiver over the panel, sgn is the signum function and Fr is the Fresnel integral

$$Fr\left(x\right)=\int_x^\infty \mathrm{e}^{\mathrm{i}\pi\xi^2/2}\mathrm{d}\xi\ , \tag{4}$$

Sound reflecting from the ceiling and ground depends on the absorption coefficient of these surfaces. The sound pressure level after reflecting from a surface is [8]

$$L_{\mathrm{p,\ refl}}=L_{\mathrm{W}}-10\log_{10}\left(4\pi d_{\mathrm{r}}^2\right)-10\log_{10}\frac{1}{1-\alpha_{\mathrm{r}}}\ , \tag{5}$$

where α_{r} is the absorption coefficient of the surface and d_{r} is the length of the transmission path. These analytical equations mentioned above will be used in Sections 3 and 4 to verify the reliability of the impulse response separation method.

2.2 The impulse response separation method

The impulse responses can be used to describe the transmission properties of a meeting room in an open-plan office, and the properties of the room such as the dimensions of the room, the positions of source and receiver and the existence of physical objects can be estimated with them [18]. Early portion of a room impulse response, which arrives within 50 ms after the direct sound, is beneficial to speech intelligibility while those arrive after 50 ms are harmful. This criterion is often referred to as the early to late energy ratio and is defined by the following equation as [18]

$$C_{50}=10\log_{10}\left[\sum_{n=0}^{n_{50}}h^2\left(n\right)/\sum_{n=n_{51}}^{n_{\max}}h^2\left(n\right)\right], \tag{6}$$

where $h(n)$ is the impulse response and n_{50} and n_{51} are the sample numbers corresponding to the 50^{th} and the 51^{st} milliseconds after the direct sound.

In general, each peak in the impulse responses corresponds to an acoustic transmission path from the source to the receiver, so the acoustic transmission paths can be separated according to the time delays due to the specific length of the particular path. Bradley has used this method to mark the components of the impulse response of the initial ceiling reflection path and the initial panel diffraction path [19]. However, only qualitative analysis was carried out in the reference. Here quantitative analysis is proposed in this paper and applied on the room impulse responses. Similar to the early to late energy ratio, the relative sound energy of a particular transmission path to the whole energy ratio can be defined as:

$$C_q = 10\log_{10}\left[\sum_{n=n_{ql}}^{n=n_{qu}} h^2(n) \Big/ \sum_{n=0}^{\infty} h^2(n)\right], \tag{7}$$

where $n_{q\mathrm{l}}$ and $n_{q\mathrm{u}}$ are the sample numbers of the lower and upper limits corresponding to the qth peak component of the impulse response.

Once the physical length of an acoustic transmission path is known, the ratio of sound energy arriving at the receiver within the time interval can be obtained from Eq. (7). Because the peaks in the measured impulse responses usually are not ideally narrow, a time interval is necessary to obtain the peak energy from the measured impulse responses (4 ms is used in the paper for the system with a sampling frequency of 48 kHz). So the upper and lower limits of the impulse response in Eq. (7) are defined as:

$$n_{q\mathrm{l}} = \left(l_q / c_0 - 0.002\right) f_{\mathrm{s}}, \tag{8a}$$

$$n_{q\mathrm{u}} = \left(l_q / c_0 + 0.002\right) f_{\mathrm{s}}, \tag{8b}$$

where l_q is the length of the qth acoustic transmission path, c_0 is the speed of sound in the air, f_{s} is the sampling frequency of the system that is used to measure the impulse responses. In actual calculation, rounding is applied to Eq. (8) as sample numbers are integers. Then the peak component of the impulse responses corresponding to the qth transmission path can be obtained by:

$$h_{\mathrm{path}\ q}(n) = h(n) R_{n_{q\mathrm{u}} - n_{q\mathrm{l}} + 1}\left(n - n_{q\mathrm{l}}\right), \tag{9}$$

where $R_N(n)$ is a rectangular windowing function which can be defined as

$$R_N(n) = \begin{cases} 1, & 0 \le n \le N-1 \\ 0, & \text{otherwise} \end{cases}, \tag{10}$$

and N is the length of the rectangular windowing function.

Eq. (7) is an expansion of the early to late energy ratio. The separation of each peak component of the impulse response leads to the separation of contribution of each acoustic transmission path, which makes it convenient to compare the contributions of various transmission paths in open-plan offices regardless of complex environments of actual rooms. Because many room acoustic parameters, such as absorption coefficient, reverberation time and insertion loss, depend on frequency, this method is further extended to octave band analyses, where 7 band pass filters with center frequencies of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz are used to analyze the impulse responses in detail. Then the relative sound energy of each particular transmission path in a frequency band is calculated by Eq. (11) as follows

$$C_{q,j} = 10\log_{10}\left\{\sum_{n=0}^{\infty}\left\{\left[h(n)R_{n_{qu}-n_{ql}+1}\left(n-n_{ql}\right)\right]*w_j\right\}^2 / \sum_{n=0}^{\infty}h^2(n)\right\}, \tag{11}$$

where * means convolution, w_j is a band pass filter designed for the jth octave band.

This calculation method contains a separation in time domain by using rectangular window functions and another separation in frequency domain by using band pass filters. Once the total sound pressure level is known, the contributions of each particular transmission path is obtained by

$$L_{q,j} = SPL_{0,j} + C_{q,j} \ , \tag{12}$$

where $SPL_{0,\,j}$ means the sound pressure level of the jth octave band measured at the receiver.

For the impulse response measured in an open-plan office, the relative contributions of each particular acoustic transmission path can be obtained from Eq. (12). Table 1 lists the steps of the proposed impulse response separation method.

Table 1 Steps of the impulse response separation method.

1. Obtain the impulse responses of an open-plan office.
2. Define the upper and lower limits of the impulse responses, and use a rectangular window to obtain the components of the impulse responses of a particular transmission path.
3. Apply band pass filters, obtain the components of the impulse responses in each octave band.
4. Compare with total energy, and obtain the sound energy ratio of a particular transmission path in each octave band.
5. Compare with the measured sound pressure level, and obtain the sound pressure level of a particular transmission path in each octave band.

2.3 Contributions of each acoustic path to STI

STI is a physical quantity representing the transmission quality of speech with respect to intelligibility, and it takes various factors such as reverberation, echoes and interfering noise into account [12]. STI is based on the concept of Modulation Transfer Function (MTF), which was introduced in 1973 [20]. The modulation reduction factor m at modulation frequency F caused by reverberation can be obtained using the impulse response [21, 22]:

$$m_{\text{rev}}\left(F\right)=\frac{\left|\int_0^{\infty} e^{-\mathrm{i}2\pi Ft}h^2\left(t\right)\mathrm{d}t\right|}{\int_0^{\infty} h^2\left(t\right)\mathrm{d}t}, \tag{13}$$

where t is the time, $h(t)$ is the impulse response, and F is the modulation frequency. Eq. (13) is valid only when the carrier signal is white noise. However, it can be regarded as a good approximation when the carrier signal is an octave band signal and the m_{rev} takes the same value for each carrier signal frequency band [22]. An additional modulation reduction factor is caused by the background noise, which can be obtained by [21]:

$$m_{\text{n}}=\frac{1}{1+10^{-SNR/10}}, \tag{14}$$

where SNR is the speech to noise ratio. Thus, the modulation reduction factor is expressed in terms of reverberation and SNR by combining Eqs. (13) and (14)

$$m\left(F_i, f_j\right)=m_{\text{rev}}\left(F_i, f_j\right)\cdot m_{\text{n}}\left(F_i, f_j\right), \tag{15}$$

where $m(F_i, f_j)$ is the modulation reduction factor at 14 modulation frequencies F_i (0.63, 0.80, 1.00, 1.25, 1.60, 2.00, 2,50, 3.15, 4.00, 5.00, 6.30, 8.00, 10.00 and 12.5) Hz and 7 center frequencies of octave bands f_j (125, 250, 500, 1000, 2000, 4000 and 8000) Hz [11].

The apparent signal to noise ratio can be calculated by [11]

$$ASNR=10\log_{10}\frac{m}{1-m}, \tag{16}$$

If $ASNR$ > 15 dB, $ASNR$ = 15 dB, and if $ASNR$ < −15 dB, $ASNR$ = −15 dB. The STI can be obtained by [11]

$$\text{STI}=\frac{15+\sum_{j=1}^{7}k_j\left[\frac{1}{14}\sum_{i=1}^{14}ASNR\left(F_i, f_j\right)\right]}{30}, \tag{17}$$

where band weighting constants k_j is 0.13, 0.14, 0.11, 0.12, 0.19, 0.17 and 0.14 in 7 octave bands with a centre frequency of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz, respectively.

To investigate the influence that each transmission path has on speech privacy, the corresponding STIs are calculated when contributions of each transmission path are removed. The new impulse response without a particular transmission path is then obtained by subtracting the separated section from the original impulse response in time domain with

$$h_{\mathrm{New}} = h(n) - h_{\mathrm{path}\,q}(n), \tag{18}$$

The new SNR without a particular transmission path is obtained by subtracting this portion of the sound pressure from the total sound pressure:

$$SNR_{\mathrm{New}} = 10\log_{10}\left(10^{SPL_{0,j}/10} - 10^{L_{q,j}/10}\right) - L_{\mathrm{Noise}} \ , \tag{19}$$

With the new impulse responses and the SNRs, the modulation reduction factor obtained by Eq. (15) changes and so do the values of STI. The contributions of each acoustic path to speech privacy in open-plan offices can then be illustrated.

3 Simulations and experiments verification

3.1 Simulations

Odeon 12.0 is used to investigate the speech privacy of meeting rooms in open-plan offices. In the simulations, the size of the open-plan office was 6.0 m × 8.0 m × 3.0 m, and the size of the small meeting room was 1.0 m × 1.0 m ×1.5 m. An omni-directional sound source with a sound power level of 80 dB in each octave band was placed at the center of the meeting room with a height of 1.0 m. The receiver was set 1.0 m outside the meeting room at the height of 1.0 m. The schematic diagram of the model is shown in Fig. 2. Fig. 3 shows main acoustic paths for sound transmitting from inside to outside the meeting room.

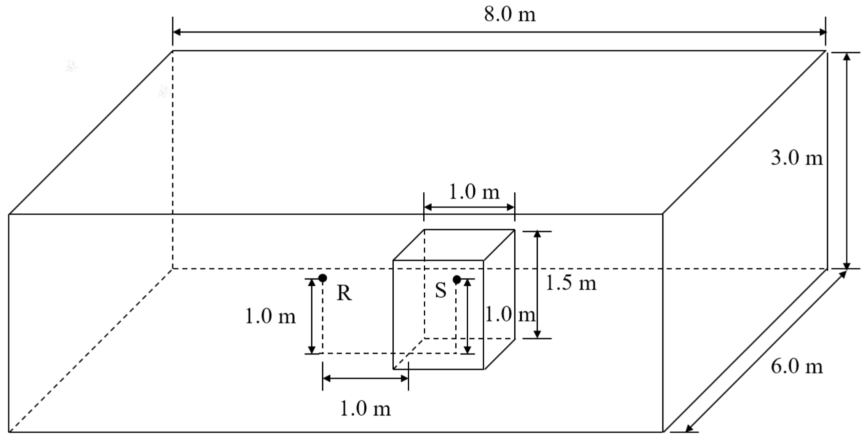


Figure 2 The schematic diagram of the simulation model.

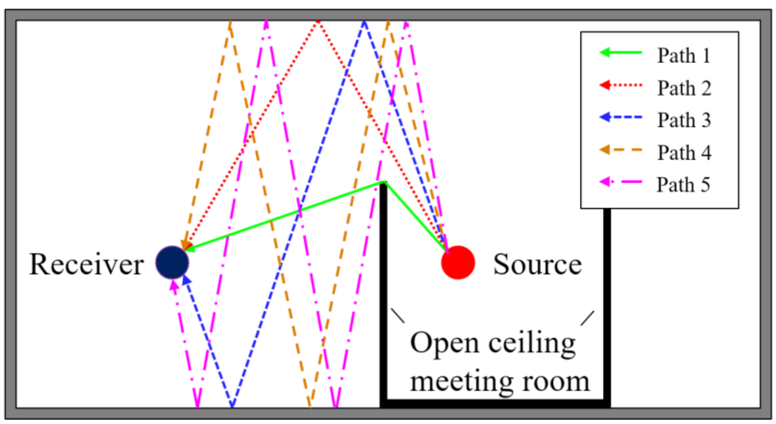


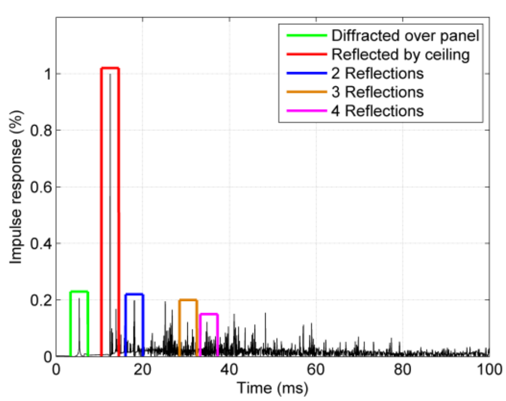
Figure 3 Main acoustic paths for sound transmitting from inside to outside the meeting room, where Path 1 is that diffracting over the panel, Path 2 is that reflecting from the ceiling, Path 3 is that reflecting twice from the ceiling and ground, Path 4 is that reflecting three times from the ceiling and ground, and Path 5 is that reflecting four times from the ceiling and ground.

Four scenarios were investigated to compare the theoretical predictions and simulation results. First, the absorption coefficient of all surfaces in the open-plan office was set at 1.0, which means there were no reflections and reverberation. In this case the only acoustic path is diffracting over the panel. Second, the absorption coefficient of the ceiling was adjusted as shown in Table 2 to approximate rigid smooth walls while others remained at 1.0 to further investigate the sound reflecting from the ceiling. Third, the absorption coefficient of the ground was adjusted to the same as the ceiling, so that the reflections from the ground can be included. Finally, the absorption coefficients of all office surfaces were set at those in Table 2 to investigate the reverberation effects of the open-plan office.

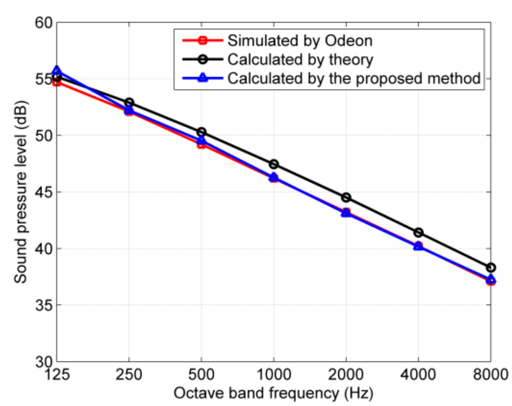
Table 2 Absorption coefficient of the room surfaces

Frequency	125	250	500	1000	2000	4000	8000
α	0.05	0.07	0.10	0.15	0.15	0.20	0.30

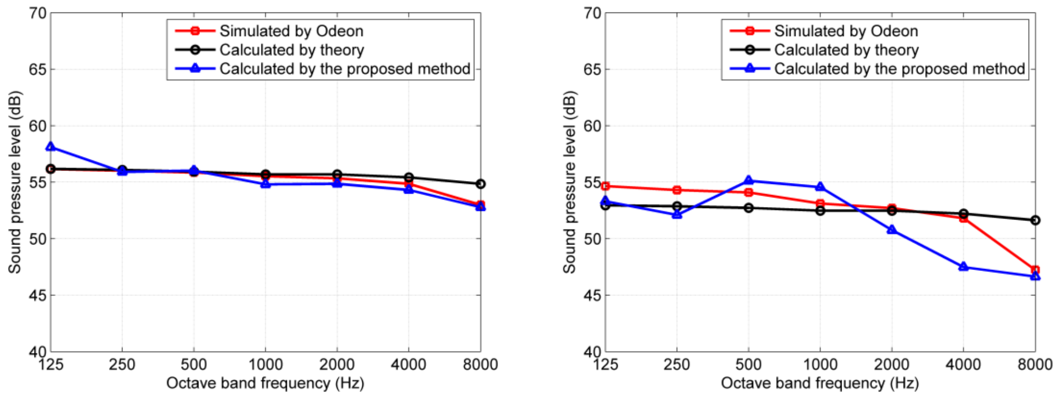
Fig. 4(a) shows the simulated impulse response obtained by Odeon with the source and the receiver at the positions shown in Fig. 2 and the absorption coefficients in Table 2 were used on all surfaces in the simulations. The peaks representing different paths are marked according to the time delays caused by the lengths of the acoustic paths. The transmission paths indicated in Fig. 3 are investigated here. The simulated and calculated sound pressure levels are shown in Figs. 4(b), (c) and (d). It is clear that the results calculated with the impulse response separation method proposed in Section 2.2 agree well with the simulation results from Odeon and the theory introduced in Section 2.1. The average error is less than 1.0 dB, and this demonstrates that the method for calculating contributions of each acoustic path in different octave bands is reliable.



(a)



(b)



(c) (d)

Figure 4 Simulated impulse response and comparisons of sound pressure levels simulated by Odeon, calculated by the theory and calculated by the proposed impulse response separation method, (a) simulated impulse response, (b) sound diffracting over the panel, (c) sound reflecting from the ceiling, (d) sound reflecting from the ground.

As mentioned in Section 2.3, both reverberation and background noise affect STIs. It is obvious that the removal of acoustic transmission paths changes the property of the room, thus leading to the change of the impulse response and the speech to noise ratio. The new impulse responses and SNRs without each transmission path are obtained by using Eqs. (18) and (19), and the corresponding STIs are obtained by using Eqs. (13) to (17). The calculated STIs corresponding to different room conditions and different background noise are shown in Table 3.

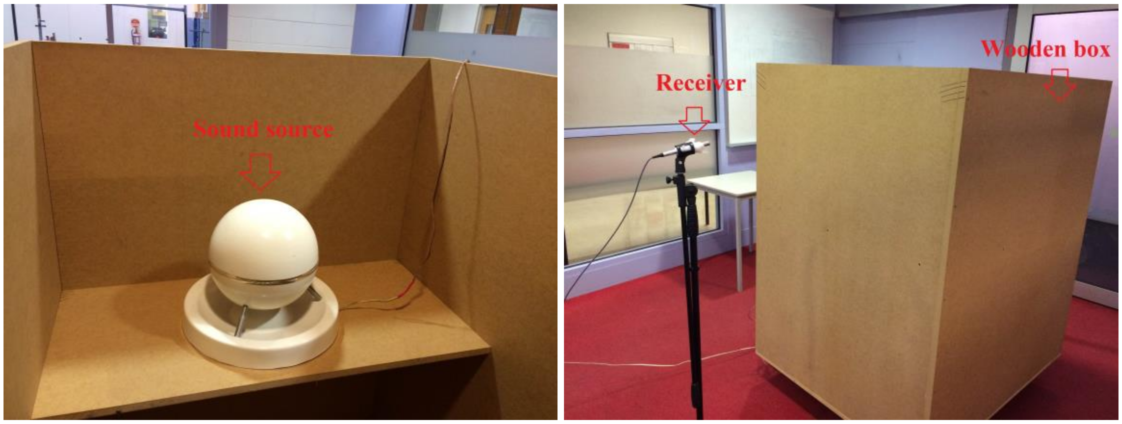
Table 3 Calculated STIs without contributions of different acoustic paths in simulation.

Path	STI under background noise (dB)		
	0	30	50
Actual room with all paths	0.7028	0.7010	0.5523
Without diffracting over panel	0.7026	0.7007	0.5500
Without reflecting from ceiling	0.7027	0.7000	0.5265
Without reflecting from ground	0.6812	0.6787	0.5243

In order to distinguish the subtle changes of STI, 4 decimals are retained here. Though these subtle changes have little effect on speech privacy, they can be used to compare the contributions of different transmission paths. For the simulated impulse response shown in Fig. 4(a), there is no background noise so the reverberation is the main factor that influences the values of STI and speech privacy. The calculated results are shown in the first column of Table 3. It can be seen that different transmission paths have different effects on STI, but it does not have great effects when there is no background noise. In order to explore the effects of background noise on STI, two conditions in which background sound pressure levels (30 dB and 50 dB, respectively) are investigated and the calculated STIs are indicated in the 2nd and 3rd columns of Table 3. It can be seen that there is barely any difference in STIs between the two conditions when the background noise is 0 dB and 30 dB. However, when background noise is increased to close to the sound pressure level of speech (around 50 dB here), STI decreases apparently, which shows that different transmission paths might have larger effect on STI when SNR is low.

3.2 Experiments

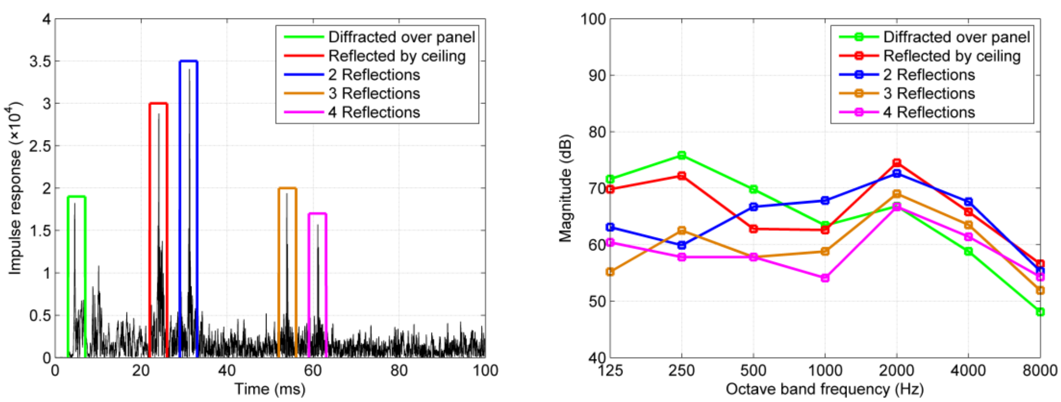
The experiments were conducted with an open ceiling wooden box in 3 different open-plan offices to investigate the contributions of various transmission paths on speech privacy. Office1 is a large empty room with dimensions of 16.5 m × 30.9 m × 5.1 m, Office 2 is a medium size conference room with dimensions of 5.9 m × 8.3 m × 2.7 m, and Office 3 is a small discussion room with dimensions of 3.9 m × 5.6 m × 2.7 m. The size of the wooden box used as the model of the open ceiling meeting room is 1.00 m × 0.74 m × 1.36 m, with a 0.74 m-high platform inside the box to represent a desk. The box is made of medium-density fiberboard with a thickness of 1.8 cm and a density of 722.9 kg/m^3. Room acoustics software Dirac (B&K Type 7841, version 6.0) was used together with a B&K USB Audio Interface ZE 0948 to measure the impulse responses. The sound source used was a semi-omni directional speaker while the receiver was a B&K Type 4166 microphone, as shown in Fig. 5.



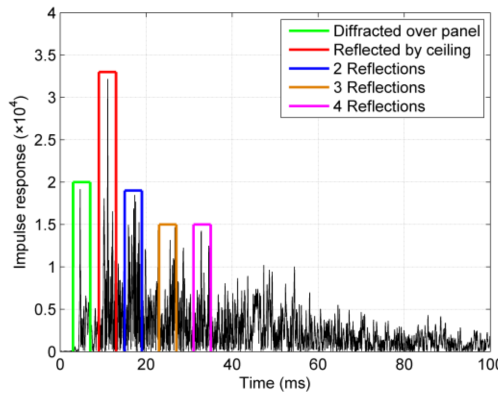
(a) (b)

Figure 5 Measurement setup, (a) the loudspeaker inside the wooden box, (b) the microphone outside the wooden box.

During the experiments, the wooden box was placed at the center of the office, and the loudspeaker was put on the platform inside the box while the microphone was 1.0 m away from the box with the height of 1.25 m. The impulse responses measured in 3 offices are shown in Fig. 6. As the reverberation is stronger in a small office than in a large office, the peaks of impulse response are more distinct in larger offices. The sound pressure levels in octave band calculated by the proposed impulse response separation method are shown in Fig. 6 as well. The marked peaks of impulse response are according to the transmission paths introduced in Fig. 3, similar to Fig. 4(a).



(a) (b)



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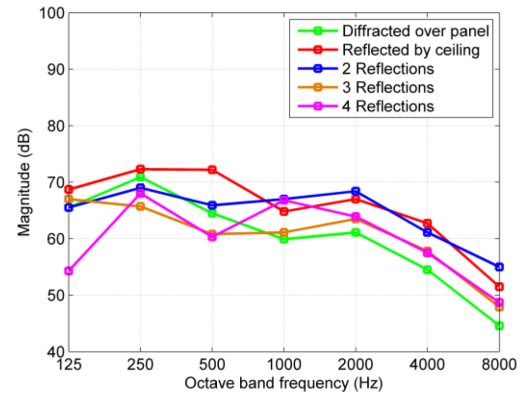

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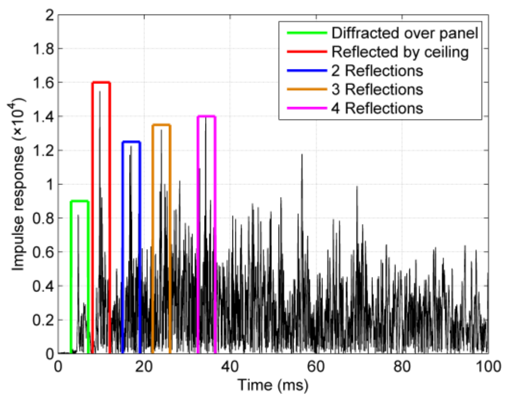

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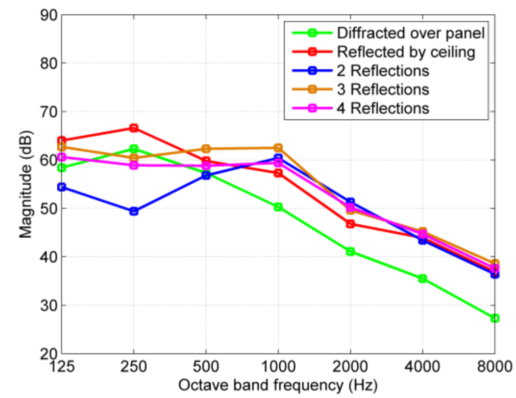


(f)

Figure 6 Measured impulse response and the calculated sound pressure level in 3 different offices, (a, b) Office 1, (c, d) Office 2, (e, f) Office 3.

In Fig. 6, the impulse responses measured are sufficient clear to be separated and the method proposed in this paper can be used to obtain the contributions of each acoustic path. Considering each transmission path in detail, the sound diffracting over the panel decays with the frequency increasing, which agrees with the trend predicted by the theory. In contrast, sound reflecting by the ceiling and ground does not agree well with the ideal conditions due to the complex environments in actual offices. The impulse response separation method introduced in this paper provides a convenient way to obtain the contribution of single transmission path in complex actual offices. Besides, it also shows that low frequency sound tends to diffract and dissipate more easily than that of high frequencies, which agrees with the physical principles.

Components of the impulse response representing each transmission path and contributions of these paths can be obtained by applying the proposed impulse response separation method. It can be used to calculate the STI according to the method in Section 2.3. The results are shown in Table 4.

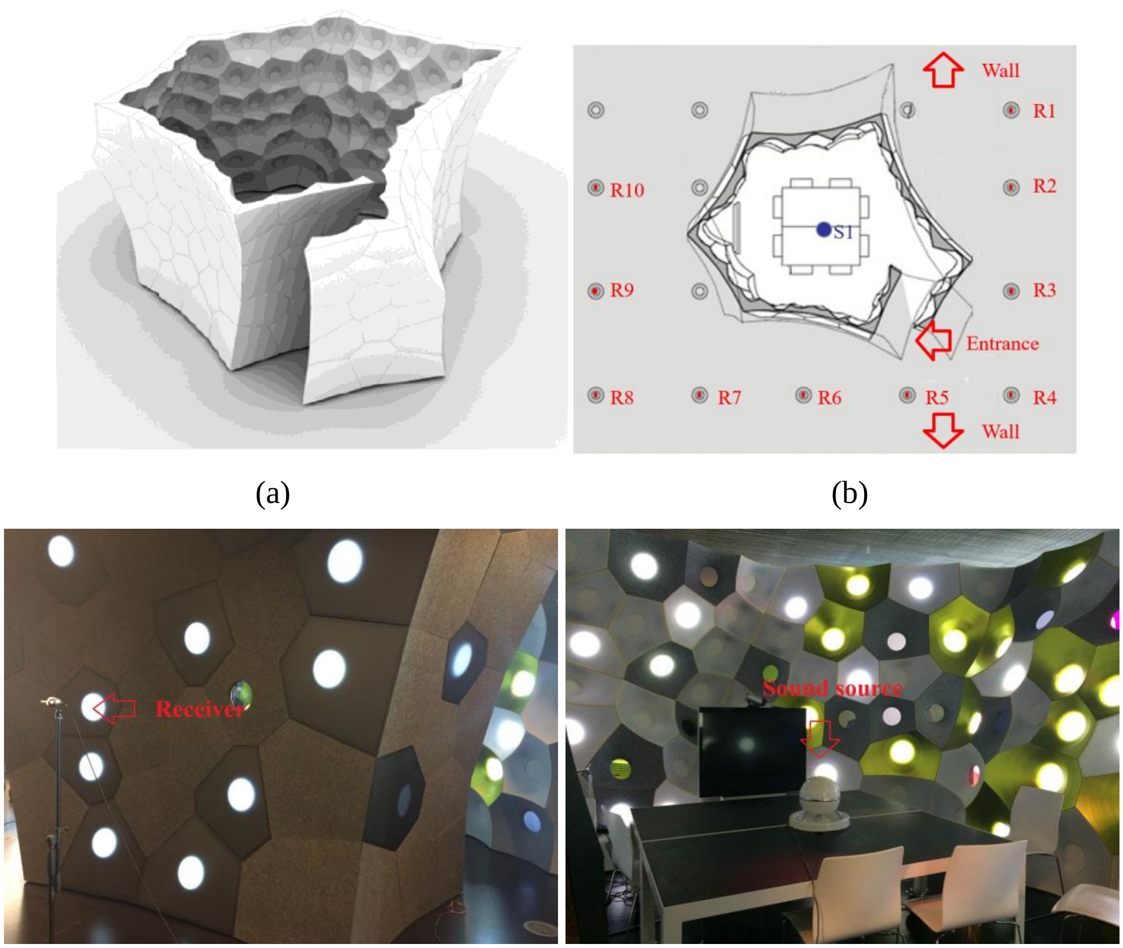
Table 4 Calculated STIs without contributions of different acoustic paths in 3 offices.

Path	Office 1	Office 2	Office 3
Actual room with all paths	0.6703	0.8096	0.6494
Without diffracting over panel	0.6570	0.8137	0.6519
Without reflecting from ceiling	0.6594	0.7990	0.6580
Without reflecting from ground	0.6671	0.7803	0.6258

As discussed in Section 3.1, lack of mask noise makes the effect of different transmission paths on STI weak. In Table 4, the values of STI just change about 0.02 with different transmission paths under consideration. For Office 1, which is a large empty office, the sound diffracting over the panel is the greatest contributor to STI while sound reflecting from the ceiling is the second most important one. For Office 2 and 3, reflecting from the ground is the most important transmission path. Meanwhile, removing the transmission path of sound reflecting from the ceiling even causes the rise of STI in smaller rooms. It is not strange as previous researches have shown that both increasing and decreasing the reflections after direct sound may cause the rise of STI [22]. So removing some transmission paths may be beneficial to the speech intelligibility and the acoustic design should be based on the actual offices to achieve good speech privacy. To sum up, the method introduced in this paper is confirmed to be useful and can provide meaningful knowledge to the acoustic design of offices.

4. Case study on the Fabpod

The Fabpod shown in Fig. 7(a) is a semi enclosed meeting room located in a large indoor open-plan office, which has non-rectangular overall geometry, non-parallel surfaces and highly articulated interior surface made from an aggregate structure composed of hyperboloid cells with different types of materials [23]. A schematic diagram of the positions of the microphones (R1-R10) and loudspeaker (S1) in the Fabpod is shown in Fig. 7(b) and photos are shown in Figs. 7(c) and (d). The double circle grid shown in Fig. 7(b) are the air-condition outlets on the ground with an interval of 2.4 m, and some of them are used as the microphones locations.

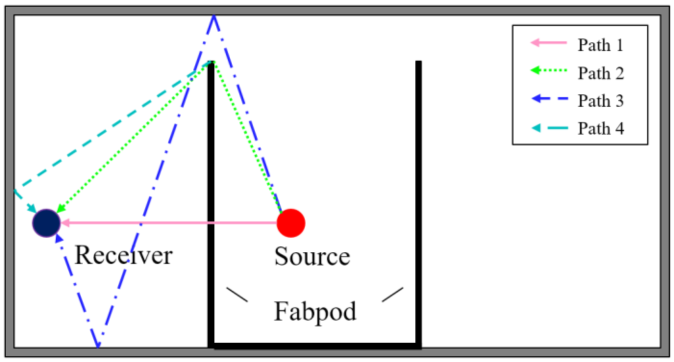


(a) (b)

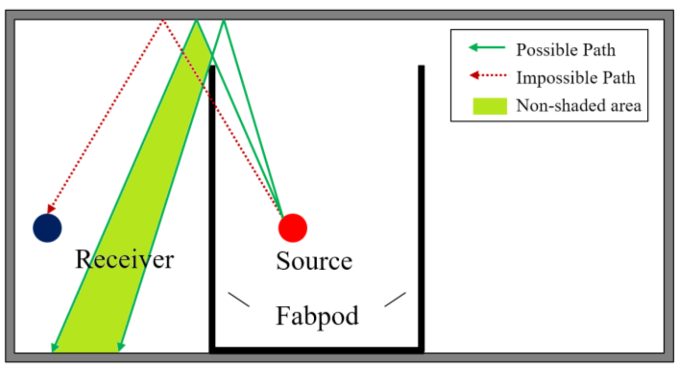
(c) (d)

Figure 7 A picture of the Fabpod located at the Design Hub of RMIT University and the experimental setup, (a) overall geometry, (b) schematic diagram of the positions of the source and receivers, (c) the receiver, (d) the sound source.

Acoustic transmission paths considered here are shown in Fig. 8(a). The surfaces of the open-plan office are called walls while the surfaces of the Fabpod are called panels to avoid confusion. Different from previous conditions, sound transmitted through the panels is taken into account as the Fabpod panel is made of lightweight materials and there is an entrance of it. Sound that arrives earlier than the diffraction over panels is considered as sound transmitting through the panel. As the panels are quite high and close to the ceiling, the zone that sound reflecting from the ceiling can reach is limited, as shown in Fig. 8(b), thus the initial reflection from the ceiling does not exist at some locations.



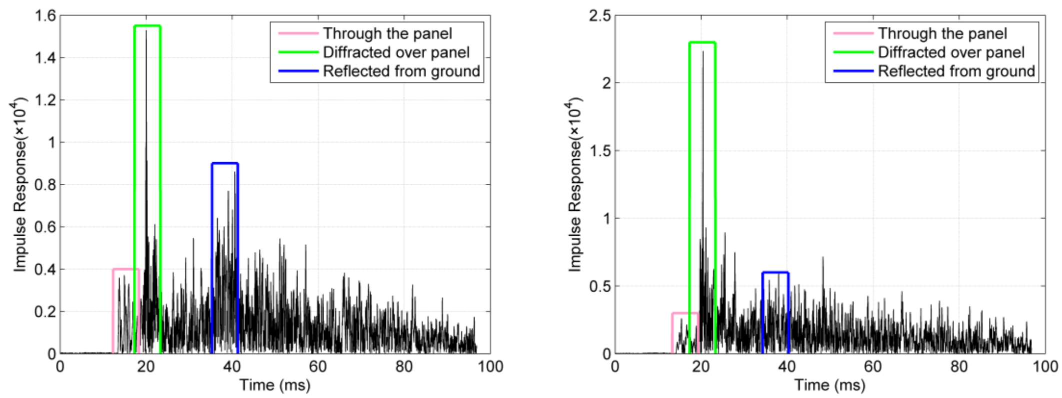
(a)



(b)

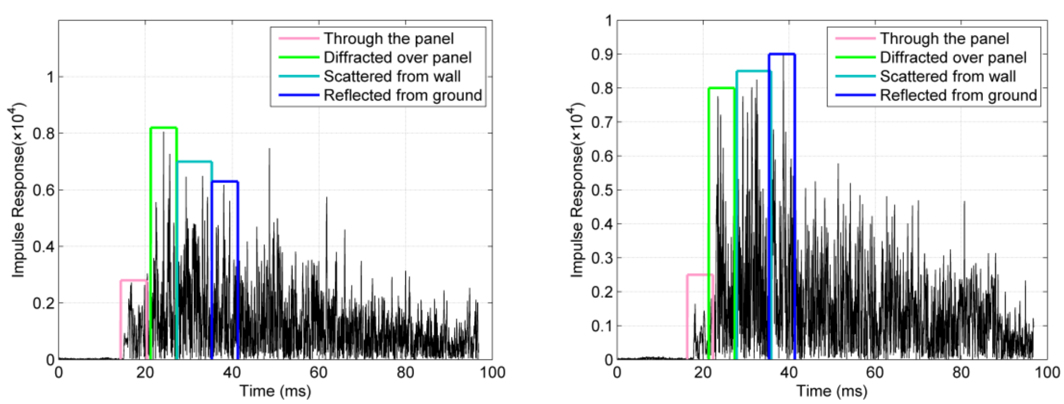
Figure 8 Acoustic paths, (a) Typical acoustic transmission paths in the Fabpod, where Path 1 is that transmitting through the panel, Path 2 is that diffracting over the panel, Path 3 is that reflecting from the walls, and Path 4 is that reflecting from the ground, (b) Paths of reflecting from the ceiling, where possible path is that can arrive at receivers after reflecting from the ceiling, and impossible path that cannot arrive at receivers.

For the receivers far away from the entrance or walls, such as R3 and R10 in Fig. 7(b), the measured impulse responses are shown in Fig. 9. It is the simplest condition and the main transmission paths are that transmitting through the panels, diffracting over the panel and reflecting from the ground. The peaks in the impulse responses that correspond to these paths are marked in Fig. 9. For the receivers near the wall, such as R1 and R8, sound scattering from the wall become stronger, as shown in Fig. 10. Here the first scattering is additionally marked while subsequent scattering are obvious in later time delay compared to the measured impulse response in Fig. 9. For the receivers near the wall and the entrance, such as R5 and R6, the sound diffracting from the entrance should be considered, which arrives before sound diffracting over the panel. The measured impulse responses are shown in Fig. 11.



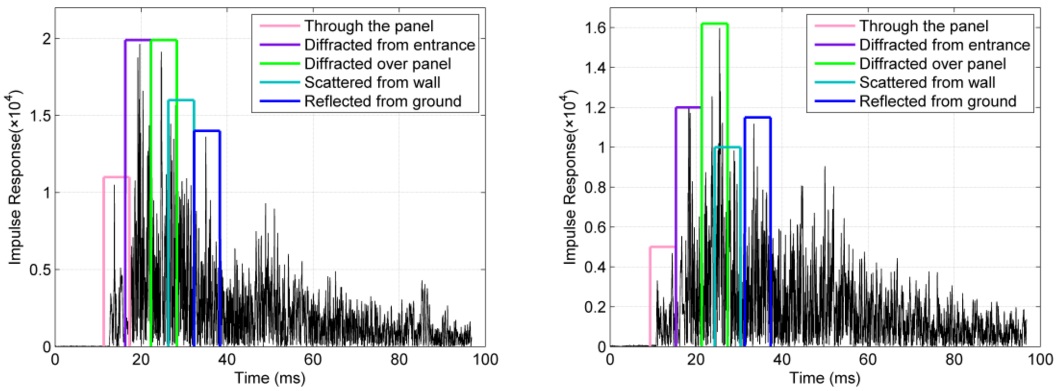
(a) (b)

Figure 9 Measured impulse responses away from the entrance or the wall, (a) R3, (b) R10.



(a) (b)

Figure 10 Measured impulse response near the wall, (a) R1, (b) R8.



(a) (b)

Figure 11 Measured impulse response near entrance and wall, (a) R5, (b) R6.

According to the proposed impulse response separation method, the SPL of each acoustic path of the Fabpod at each receiver are calculated and shown in Table 5 and the results in octave bands are omitted for brevity. It is clear that sound transmitting through the panel contributes the least in all the paths while the sound reflecting from the ground is the most important contributor in Fabpod. The sound scattering from wall is important while the receivers are close to the walls of the office. In contrast, the sound diffracting over the entrance seems not as large as the sound reflecting from ground while the receivers are close to the entrance.

Table 5 Calculated SPL of different acoustic paths by proposed method.

Paths	Receivers									
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Through the panel	67.6	74.9	71.6	69.8	76.3	72.5	71.3	70.0	69.8	68.9
Diffracted from entrance	-	-	-	72.4	82.2	78.7	77.7	-	-	-
Diffracted over panel	76.9	79.8	76.6	79.9	85.7	84.6	81.6	72.5	82.3	78.0
Scattered from wall	80.8	-	-	80.5	86.4	85.0	82.6	78.1	-	-
Reflected from ground	82.0	81.2	79.6	81.3	87.4	86.0	83.6	81.1	84.5	79.7

The contributions of each acoustic path to STI are calculated as well, and the results are shown in Table 6. The results at R2, R3, R9 and R10 exclude the influence of the wall and entrance. It is clear that sound transmitting through the panel is the least important contributor in this case since the insertion loss of the panel is high. The STI without sound diffracting over the panel is about 0.005 lower than that without sound reflecting from the ground at R2 and R3 while the results are opposite at R9 and R10, which mainly results from the existence of the table near R9 and R10. Other 6 receivers take the influence of the walls into account. The contribution of the sound scattering from the walls to speech privacy is similar to sound reflecting from the ceiling. In addition, 4 receivers near the entrance (R4, R5, R6 and R7) take the sound diffracting from the entrance into consideration. It can be seen that the contribution of sound diffracting from the entrance are different at different receivers. Sound diffracting from the entrance has the greatest influence on STI at R5 (up to 0.02), because it is the closest receiver to the entrance. Diffracting from the entrance is the most important path for R5, but it no longer the most critical one at farther receivers.

Table 6 Calculated STIs without contributions of different acoustic paths in Fabpod.

Paths	Receivers									
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Actual room with all paths	0.6872	0.6939	0.6933	0.6421	0.7317	0.6980	0.6615	0.6874	0.6560	0.6917
Without through the panel	0.6858	0.6925	0.6914	0.6416	0.7307	0.6973	0.6606	0.6870	0.6558	0.6912
Without diffracting from entrance				0.6396	0.7135	0.6901	0.6535		-	-
Without diffracting over panel	0.6822	0.6830	0.6845	0.6356	0.7163	0.6880	0.6546	0.6806	0.6446	0.6806
Without scattering from wall	0.6828			0.6328	0.7239	0.6871	0.6549	0.6799	-	-
Without reflecting from ground	0.6756	0.6798	0.6788	0.6321	0.7209	0.6913	0.6531	0.6811	0.6475	0.6854

In summary, for this special open ceiling meeting room in the open-plan office, the contributions of the transmission paths are related to the position of receivers. For most receivers, sound reflecting from the ground contributes most to the speech privacy. Laying absorption materials on the ceiling and ground can decrease the STI. Sound scattering from the walls is the second important contributor while the receivers are near the wall, and moving the Fabpod to an empty office and away from the wall can improve the STI. Diffracting from the panel is another important path and increasing of the height and width of panel shall decrease its contribution and improves the STI. The entrance is not necessarily a vital concern as it does not have much influence when the receiver is away from the entrance. Besides, sound transmitting through the panel exits but is very weak and can almost be ignored. On the other hand, removing a single transmission path does not affect significantly when the background noise is low. All these factors are important to achieve better speech privacy performance in open-plan offices.

5 Conclusions

An impulse response separation method is proposed to investigate the contributions of different acoustic paths of open ceiling meeting rooms on speech privacy in open-plan offices in different octave bands. The method is validated by comparing with the simulation results obtained by Odeon and the theoretical predictions, and is further verified by the measurements carried out in 3 different offices. Finally, the proposed method is applied to the Fabpod, a semi enclosed meeting room located in a large indoor office, to obtain the relative contributions of different acoustic transmission paths to its speech privacy and demonstrate the implementation of the proposed method. The feasibility of the proposed method is demonstrated and the method is useful for designers to improve speech privacy in open plan offices.

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