Automatic Evaluation of In-Car Communication Systems

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Abstract

Due to high background noise and sound absorbing materials the communication between front and rear passengers in a car is often difficult. In-car communication (ICC) systems distribute the seat-dedicated microphone signals via the sound system in order to improve speech intelligibility. Due to interfering signals and the closed-loop operation of the ICC system, various signal processing techniques are required to reduce echoes and noise and to prevent instability of such a system.

In this contribution a methodical evaluation of an ICC system and its incorporated signal processing schemes is presented. It considers different requirements for both speaking and listening passengers. The evaluation is performed with three types of systems or setups. The first one is an "ideal" ICC system. Here, a simulated system without any noise or feedback problem is computed in real-time and presented to listeners and to the measurement equipment. This "ideal" system is used to obtain suitable parameter settings like the maximum desired gain for instance. Furthermore, a real ICC system is evaluated, in order to analyze the achieved speech intelligibility and system quality. Finally, all measurements are performed without any ICC system, to obtain a basis for comparison.

Introduction

In limousines and vans communication between passengers in the front and in the rear may be difficult – especially if the car is driven at medium or high speed, resulting in a large background noise level. Furthermore, the driver and the front passenger speak toward the windshield. Thus, their speech is hardly intelligible for those sitting behind them. To improve the speech intelligibility the passengers start speaking louder and lean or turn toward the listening communication partners. For longer conversations this is usually tiring and uncomfortable. Another way to improve the speech intelligibility within a passenger compartment is to use an ICC system [3]. Such systems record the speech of the speaking passengers by means of microphones and improve the communication by playing the recorded signals via those loudspeakers that are located close to the listening passengers. Fig. 1 sketches the structure of a simple ICC system aimed at supporting only front-to-rear conversations (for the opposite direction a similar structure is applied) with one microphone and one loudspeaker. As it is clearly visible in Fig. 1, ICC systems operate in a closed electro-acoustic loop. The microphone picks up at least a portion of the loudspeaker signal. If this portion is not sufficiently small, sustained oscillations appear, which can be heard as howling or whistling. The howling margin depends on the output gain of the ICC system as well as on the gains of the analog amplifiers V_{Mic} and V_{Ls}. For this reason all gains within the system need to be adjusted carefully.

To improve the stability margin, signal processing such as beamforming, feedback and echo cancelation, adaptive notch filtering, adaptive gain adjustment, equalization, and nonlinear processing can be applied. A few basic processing units are already depicted in Fig. 1.

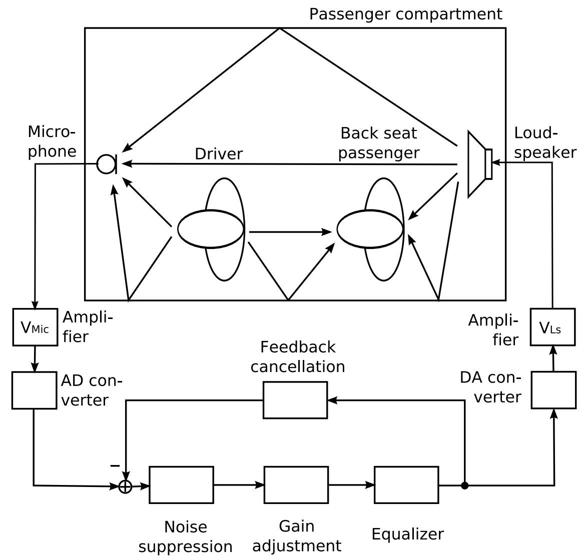

Figure 1: Structure of a elementary ICC system

In contrast to hands-free telephones or speech recognition engines, no methods for evaluating the quality of ICC systems have been standardized and only a few have been published [5] yet. Thus, evaluation is not as easy as in other speech and audio applications. Before subjective and objective evaluation are described, the boundary conditions for an ICC system are discussed in the next section. Finally, some measurements as well as subjective tests (performed in a car equipped with an ICC system) are presented at the end of this contribution.

Boundary conditions

When designing or evaluating an ICC system a wide range of limiting conditions and system demands will appear. In order to understand the origin of these demands a few phenomena (physical or psychoacoustic) will be described. On the one hand there is the system gain which is limited by the system feedback and other conditions. And on the other hand there are the delay requirements which affect the sound quality and the spatial localization.

Amplification requirements

For a sufficient signal enhancement a certain amplification is assumed. For the ICC system this value is bounded by the feedback margin. It can be increased by adequate signal processing, e.g. feedback suppression. An important question is how much "enhancement" (in terms of amplification) is required. In most cars the speech intelligibility is good or at least sufficient for the communication from rear to front if the car is not driving. In this scenario an ICC system would make the car sound more reverberant and reduce the communication quality.

However, things are different for the communication from front to rear especially at medium and high speed.

Because of the the directionality of a human head – depicted for two frequency ranges in Fig. 2 – it is harder to understand someone from behind than it is during an eye to eye conversation. For frequencies between 1400 Hz and 2000 Hz an attenuation of more than 10 dB related to the front direction, which is denoted by 0° (see Fig. 2), can be measured.

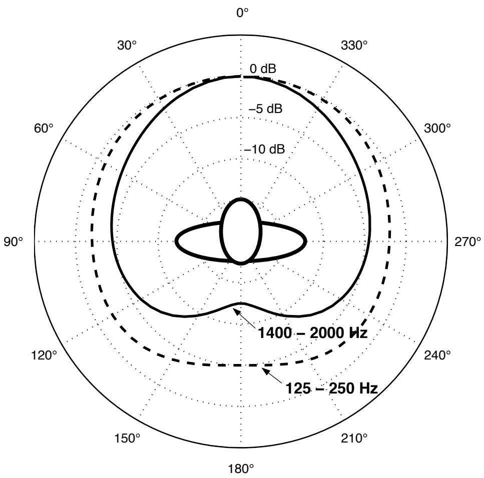

Figure 2: Average directionality of a speaking human head (according to [4]).

Moreover, for higher speeds the background noise inside the car is increasing. Car noise results from a large number of sources. The main components are engine noise, wind noise, and rolling noise. When a car accelerates from 0 to 150 km/h the power of the background noise increases by more than 30 dB at nearly all frequencies. Fortunately, an ICC system does not have to compensate for the full amount of the noise power difference between stand-still and high speed, because of the so-called *Lombard effect*. Any person who speaks in a noisy environment will automatically alter the speech characteristics in order to increase the efficiency of communication over the noisy channel. As a result the overall speech level rises with increasing background noise power. Rates of about $0.3 \ldots 1$ dB of speech power per decibel increase of background noise have been reported [2].

For answering the question about the required gain of ICC systems, it is not sufficient to sum-up the particular attenuations and noise level increments because the acoustic situation is changed significantly by the system (the speaker is supported by a number of loudspeakers). But it gives a dimension for the gain requirements.

Delay requirements

It is important to note that apart from the stability margin, a few other limiting conditions have to be considered. One of these is that visual and acoustic source localization should match. This is especially a problem for the rear passengers as they see the front passengers in front of them. However, if the rear loudspeakers are installed behind the rear seats and the gain of these loudspeakers is too high, the acoustic localization indicates that the speaking person is behind the listening one. This mismatch of different senses causes a very unnatural impression of the communication. To overcome this problem the gain of the rear loudspeaker has to be limited according to the delay between the primary source (e.g. driver) and the secondary source (e.g. loudspeaker in the rear). The amount of amplification until the localization mismatch effect appears is given by the so-called *precedence effect* [1]. Results of psycho-acoustic experiments show that the secondary source does not affect the acoustic localization, even if it is louder than the primary source up to 8 dB, if the delay time between these signals does not exceed 15 ms. These results correspond very well to experiments made within cars.

Furthermore, a higher delay also corrupts the car sound quality. For the ICC system delay is caused by the used hardware (AD/DA conversion, DSP-amplifier) and the signal processing. For higher delays the car sounds reverberant for the listening person and it gets very annoying for the speaking person as he can hear himself.

Gain subjected to delay

For the examination of ICC system quality and improvement of speech intelligibility the system gain and the system delay have to be considered together. The ICC system gets instable for higher gains, but a high gain level is required for a noticeable communication improvement. A higher system delay caused by the used hard- and software decrease the sound quality by making the car sounding reverberant, but it allows the use of more powerful signal processing or cheaper hardware. Moreover, problems like rising background noise level, difficult acoustic localization, echoes disturbing the passengers, etc. should be considered too.

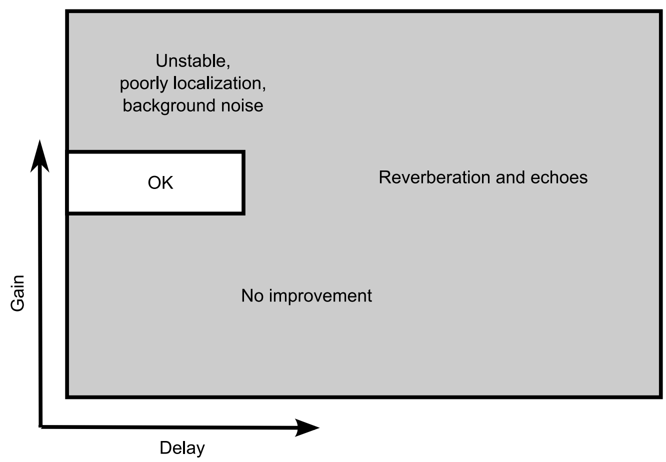

Figure 3: Correlation of system gain and system delay. The part labeled with "OK" is the preferred operating range.

Fig. 3 shows the correlation of system gain and system delay. Only the small part, labeled with "OK", shows the preferred system operation range. This operation range strongly depends on the individual positions of the microphones and loudspeakers and the used signal processing.

For a system with better feedback cancelation, the upper threshold would move upward.

Subjective evaluation

Although this correlation depends on the used ICC system, the following section will present a subjective evaluation of an ICC system installed in a Mercedes S-class to prove this interrelation. The subjective test presented here determines the total ICC system gain with respect to the system delay. In particular, the largest acceptable system gain will be analyzed on the basis of a real ICC system. For comparison of the achieved quality an ideal ICC system will be evaluated as well.

Real system

A listening person evaluates the ICC system quality on the rear seat directly behind the speaking person at the passenger's position. The speaking passenger is simulated by an artificial mouth loudspeaker (loudspeaker with approximately the same radiation pattern as a human head), which plays back a clean speech signal (several male and female speakers) at an appropriate level. A microphone is placed above the speaker at a distance of 25 cm on the ceiling. The proband in the rear seat adjusts the total system gain of the basic ICC system (containing a high-pass filter, feedback suppression, and an equalizer). The total system gain has been noted for:

- ICC system just noticeable,
- preferred system gain (preferred operation range),
- ICC system gets annoying.

The test has been repeated for different system delays.

Ideal system

The evaluation of the real ICC system shows that there are problems for higher system gains. Especially the feedback causes strong distortions when operating the system close to the stability margin. But even at moderate system gains, the amplified background level and the feedback based reverberation affects the system quality as well. To avoid these problems an ideal ICC system has been designed. As one can see in Fig. 4 the microphone signals in the ideal ICC system are replaced by simulated microphone signals. Therefore, the artificial mouth loudspeaker signal have to be convolved with the MEM (mouth-enclosure-microphone) impulse responses. The required MEM impulse responses need to be measured in advance. Consequently the ideal ICC system has neither feedback nor increasing background noise problems.

Results of subjective evaluation

The subjective evaluation is accomplished by four ICC system established test persons (the high expenditure of time determines the size of this test group). The test persons adjust the preferred total system gain level – for three afore mentioned thresholds – while sitting in a car driven at 100 km/h. The test has been repeated for different system delays. Without additional delay the time between the direct and the reproduced sound at the ear of the test person is 6 ms. An additional delay has been added with 0, 5, 10, 15, 20, 30, and 50 ms in order to evaluate the influence. Both the real and the ideal ICC system have been tested.

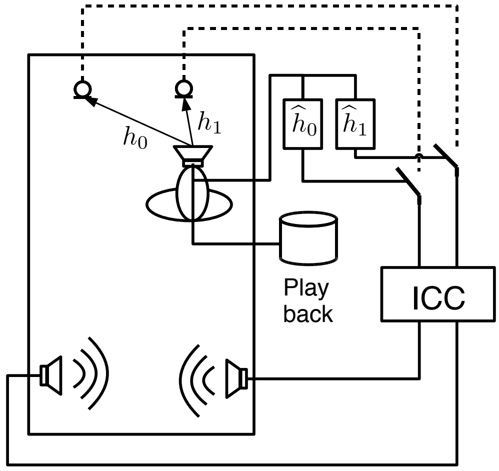

Figure 4: "Ideal" ICC system: the microphone signals are replaced by a clean speech signal convolved with appropriate impulse responses.

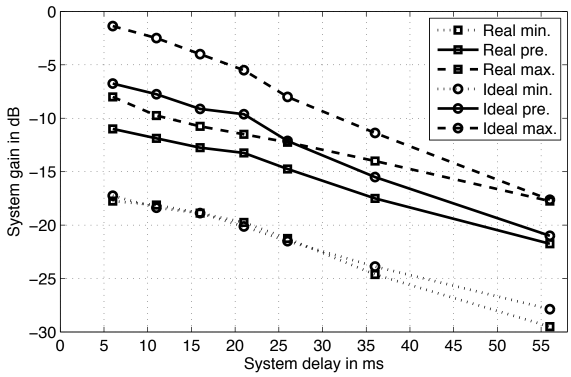

Figure 5: Results of the subjective gain level evaluation at 100 km/h. The listening person determines the total desired ICC system gain.

Fig. 5 depicts the results of this evaluation. The dotted lines show the minimum system gain level, below this level the ICC system is not noticeable. The solid lines depict the preferred total gain level for this system. The dashed lines show the upper gain level, where the ICC system gets annoying. Lines marked by squares present the results of the real and lines marked by circles of the ideal ICC system. As you can see the dotted lines are very similar. But with increasing gain level the difference between the real and ideal system gets bigger. The gain of the real system is bounded by the stability margin, which does not exist for the ideal system. For additional delay the played back signal gets more annoying for higher gain levels. Therefore, the gain levels are declining for rising delay.

The result of this evaluation is that about 5 dB more total ICC system gain is needed for the real system at the back-seat position, for a acceptable delay up to 15 ms. The determined gain values present a basis for further evaluations with an enhanced ICC system.

Objective evaluation

Subjective tests have two main drawbacks: on one hand they are quite time consuming — and thus expensive — and on the other hand small differences between different systems or algorithmic versions are quite hard to evaluate with a small group of listeners. For this reason, objective evaluation methods should be applied, not as a replacement but as a supplement to subjective tests.

One way of measuring the improvement of the speech quality due to an ICC system is to measure the impulse or frequency responses from the mouth of the speaking passenger, say the paassenger, to the ears of the listening passenger, e.g. the right rear passenger. Such measurements should be performed with and without the ICC system. For measurements with the ICC system all the system parameters need to be set to the evaluated values and adaption activity needs to be stopped to be able to measure the system impulse response. An artificial mouth loudspeaker and a head-and-torso simulator with ear-microphones should be used for this purpose.

Application of objective evaluation

By means of the measured impulse response the following system parameters can be determined automatically: system delay, reverberation time, and frequency response. Fig. 6 depicts the frequency response between the artificial mouth loudspeaker at the passengers position and the left ear-microphone at the seat behind the passenger with real, with ideal, and without the ICC system. It can be used for the evaluation of the ICC system gain. For this purpose the ratio between the frequency response with and without system need to be calculated. Furthermore, the calculated frequency response can be used for the determination of the preferred equalizer settings.

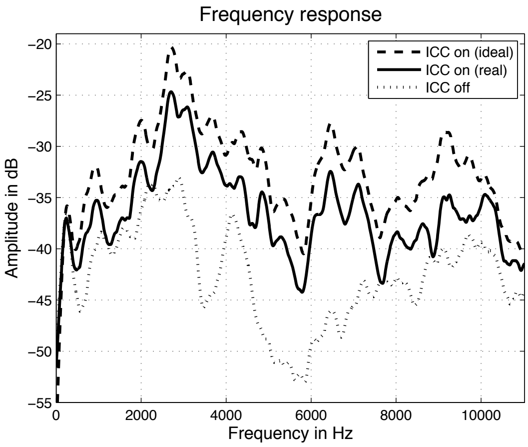

Figure 6: Frequency response at the listening person's left ear.

A conclusion about the system reverberation can be made on the basis of the reverberation Time T_{60}, which can be derived from the corresponding impulse response [4]. The larger the system feedback, the higher the reverberation time $T_{60,\mathrm{real}}$ is compared to $T_{60,\mathrm{ideal}}$ or $T_{60,\mathrm{off}}$ without feedback. Fig. 7 depicts energy decay curves calculated from the corresponding impulse responses. The reverberation time T_{60} can be determined from the gradient of the decay curve. A ratio of these values can be used for evaluation of the degradation of the system reverberation.

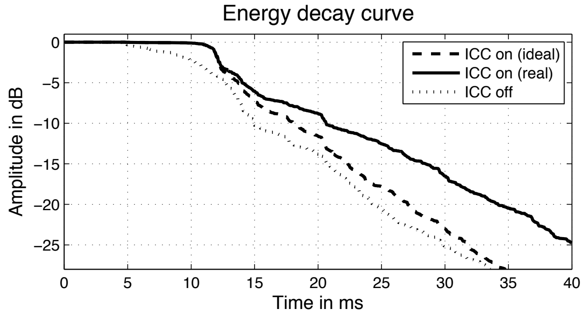

Figure 7: Energy decay curve of the impulse response at the listening persons left ear.

Further parameters can be determined due to the measured impulse response. Moreover, impulse responses at the other possible listening positions as well as to the speaking position need to be evaluated, too.

Conclusion

An ICC system is needed to improve the communication quality in the car. Thereby the speech enhancement and the system quality depend on the timing and the power of the reproduced signal. To illustrate this the influence and the interrelation between the system gain and the system delay have been depicted. The interrelation has been subjectively evaluated for a real and an ideal ICC system. From there the desired working range and the appropriate system parameters have been determined. For this parameters an objective system evaluation has been performed by means of the impulse response, concerning the ideal and the deactivated system. Because the desired working range depends on many criteria, like background noise, microphone position, and the used signal processing, more subjective tests are needed for an improved objective evaluation of an ICC system.

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