WHY IS GOOD SPEECH INTELLIGIBILITY IN MOSQUES A CHALLENGE?

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1 INTRODUCTION

Preaching has been an integral part of most prayers in mosques since the very first days of Islam. This is in contrast to the orthodox and catholic churches, where the spoken word was becoming important only in the last 500 years, before which services took place in Latin or Greek languages.

Prior to the invention of loudspeakers, speech intelligibility in large sacral buildings was commonly bad. In this regard, pulpit ceilings, for example, were introduced in cathedrals and large churches to support the pastor's voice. After converting it from a church into a mosque in 1453, *Hagia Sofia* in Constantinople, Turkey used to employ one or two "human repeaters" in a certain distance to each other along the way between the *imam*[1] and the furthest row, whose job was to repeat the *imam*'s words in an attempt to enhance intelligibility. Sound systems have been introduced in sacral buildings since the thirties of the last century. In cathedrals and churches in Europe, passive line arrays have been used until the nineties installed at the numerous pillars there. In North America at that time, horn loudspeakers were used in almost all church spaces.
In cases where pillars were available in mosques at the same density like in churches, they were used as installation locations too. More difficult was the situation in mosques with large enclosed spaces below huge domes, where classical line arrays and horn loudspeakers were employed with usually unsatisfactory results with respect to speech intelligibility. In the last years a lot of efforts have been undertaken to improve the situation of speech intelligibility in sacral buildings. This is certainly similar to all other public places like theatres, cinemas, and stadiums etc., where the sound quality at home coming from CD, DVD players and also radio and TV sets raised the listeners' expectation about sound quality. A congregation member expects now to have no difficulty understand every word spoken by, for example, the *imam*, the pastor or the rabbi, and starts to complain, if he/she does not grasp effortlessly all words.
First research work to improve the sound quality in mosques was carried out in the mid-nineties/1,2/, which focused on improving the room acoustic properties of the space and the quality of the sound system as well. Ph.D. researches were even dedicated to that purpose/3/.

The following sections will explain the specific components influencing the room acoustic properties in a mosque. Furthermore the use of different sound system solutions is explained. In this context, the need of associated simulation for room acoustic as well as sound system design is highlighted.

2 BASIC ELEMENTS IN MOSQUES

A mosque is a place for religious activities in Islam including praying, preaching and teaching. There is mainly one source of speech information, which is the voice of the *imam*, and a congregation of male worshippers in the ground floor and, usually, less female worshippers separately on a gallery or in other designated areas. The *imam* speaks or recites close to the *qibla*[2] wall in front of the

[1] *Imam is the leader of the Muslims during prayers. This can be a title as well for renowned Islamic scholars.*

[2] *Qibla is the permanent direction, in which a Muslim aims at during prayers, which is the direction of the Kaaba in Makkah.*

mihrab[3] or on the *minbar*[4], Figure 1. In the older mosques built 100 years or more ago, no acoustic treatment of walls and ceilings was common, but only carpet covered all floor levels.

Beside the hard surfaces of walls and ceilings, one or more domes were/are typical architectural design features of mosques. It is believed that this architectural style started to dominate after the conquest of Constantinople in 1453, when the Byzantine church *Hagia Sofia* with its huge dome and its other minor ones was converted into a mosque. This construction was becoming a prototype for new mosques in the following centuries and, somehow, continues to be so until today.
Domes in rooms may create sound focusing, which can be of negative effects depending on the shape of the dome. This was not known from the beginning, but now such negative impacts on sound distribution in mosques may be avoided by selecting the right height and shape of the dome.
Before the introduction of electricity and acoustic transducers like microphones and loudspeakers, it was not unusual that the speech intelligibility was bad, especially in the back rows of larger mosques. The elevated minbar position did help to radiate sound to further worshippers sitting away, but this had its limits. Today, simulations as well as experience are showing that the human voice may create SPL values above a threshold of 40dB in a distance of up to 25m. However, in mosques with reverberation times between 6s and 10s, the speech intelligibility will drop to bad levels at distances of maximum 10m. Therefore, it may be assumed that in the old days the *imam* could be understood in a radius of only 10m.
This limit of 10m distance from the *imam* was significantly extended since the use of sound systems in mosques, which was especially remarkable after WWII. Nevertheless, this was based quite often on trial and error. Loudspeakers could have been even selected and installed by a committee of the mosque congregation or the mosque administration without any basis for expecting good or bad intelligibility results other than personal impressions and wishful thinking of laypersons. In smaller mosques, the loudspeakers have been installed mostly on the existing numerous pillars, Figure 2.
In some larger venues, special grids are used to install loudspeakers next to light fixtures, Figure 3.
All these attempts don't necessarily work well, where the reverberant field in the mosque space is partially excited by the large number of loudspeakers and the speech intelligibility is only good close to the loudspeakers.
Since 20 years now, better sound systems are expected in mosques too, as the trial-and-error method has been replaced by judging the expected sound quality in advance by computer simulation, and in this way the design of a new installation can be verified, the reverberant field can be minimized and the direct field can be boosted.

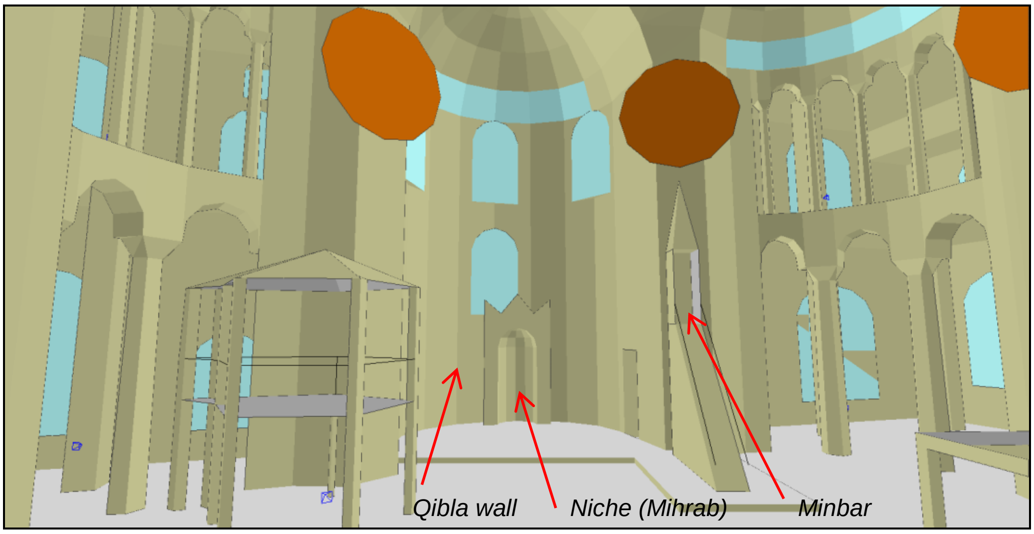


Figure 1 View into the EASE model of Hagia Sofia in Istanbul

[3] Mihrab *is a semi-cylindrical niche in the front wall of a mosque, which is used to define the qibla direction.*

[4] *Minbar is a pulpit in a mosque, from where the imam delivers sermons.*

3 NEEDED DATA FOR COMPUTER SIMULATION IN MOSQUES

Speech is intelligible, when the following three factors effectively work together;

1. The direct-to-reverberant ratio is adequate;
2. The signal-to noise ratio is adequate;
3. The signal level is adequate for perception, but not too loud with negative signal masking effects.

The first factor is dependent on the transduction and directional capability of the loudspeaker system of delivering enough direct energy at the listeners' ears without exciting significantly higher diffuse field, which is in turn function of the room acoustics as well.
The second and third factors are independent of room acoustics, but rather dependent basically on the loudspeaker system and its capability of mounting above noise levels and integrating with the requirements of psychoacoustics.

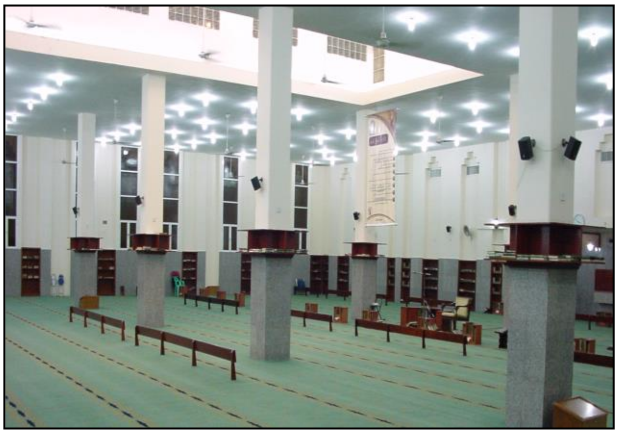


Figure 2 Decentralized loudspeaker arrangement typical in smaller mosques

What is then needed to realize good speech intelligibility in a mosque? The computer simulator needs enough and accurate data about the following two categories, in order to deliver plausible predictions of speech intelligibility;

- Room acoustic design
- Sound system design

Only by appropriate reverberation ratios and by installing a well-designed sound system, the speech intelligibility may be brought up to a needed level. Strong reverberation and poorly designed sound systems will be associated most probably with bad intelligibility. The authors want to illuminate both room acoustic and sound system design components a little bit closer.

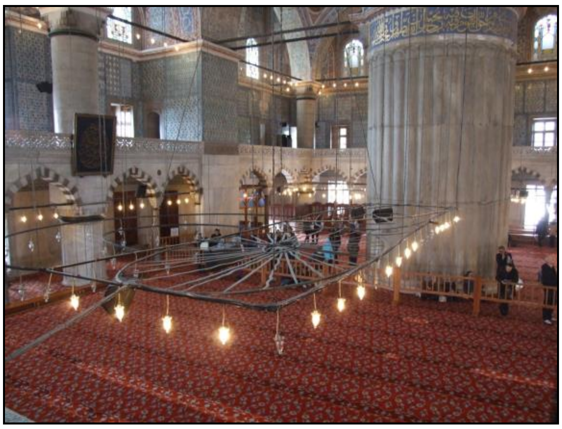


Figure 3 Decentralized loudspeaker arrangement in the *Blue Mosque* in Istanbul

4 ROOM ACOUSTIC DESIGN IN MOSQUES

Here, a distinction is made between the following scenarios;

a) Existing mosques under monument protection

b) Existing mosques under reconstruction

c) New mosques

4.1 Existing mosques under monument protection

In these cases, wall and ceiling areas cannot be acoustically treated. Therefore, the only possible “treatment” in the mosque can be carpet on the floor. The carpet has two major functions; one is to provide a certain level of comfort for the worshippers during prayers, and the other job is to provide sound absorption.

Thus, the selection of the right carpet material is important, i.e. the higher the absorption coefficients the less significant the resulting reverberation field. To understand the interaction between absorption and the carpet type, the results of the measurement of different types of carpet are considered, Figure 4 and Figure 5. Figure 4 shows measurements done in 2005 for the *Grand Mosque* in Abu Dhabi in comparison with a newer carpet together with a new underlay intended for another project.

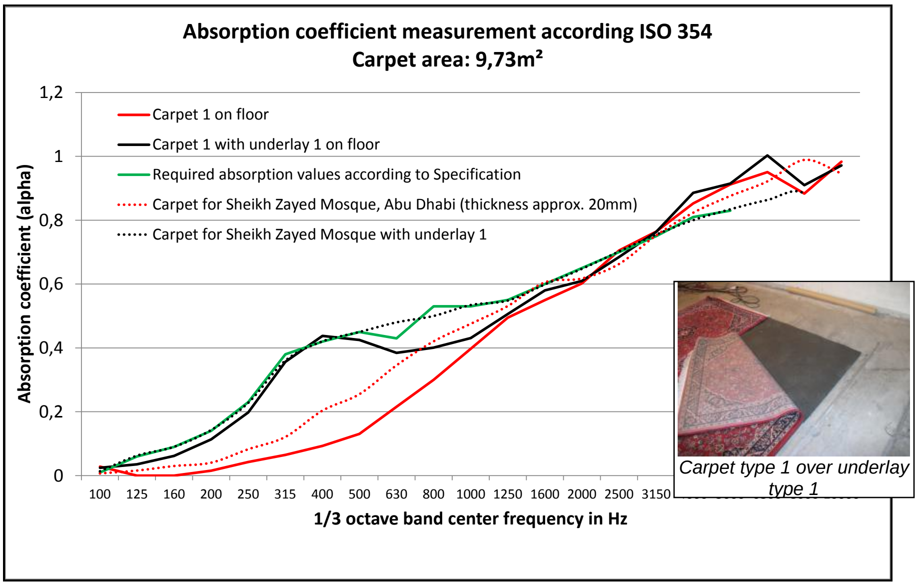


Figure 4 Absorption coefficients vs. frequency

It is visible that the carpets alone, i.e. without any underlay, don’t show significant absorption below 1000Hz, while with an underlay (12mm thick rubber-based material) the carpet and the underlay act together as a spring-mass-system and the absorption is increased in this way significantly to come closer to specifications in the new project.

Another carpet type 2 has been compared with the above-mentioned carpet type 1, with and without different and new types of underlay, Figure 5. Also the underlays alone have been measured separately.

The results show that only the use of underlays makes significant acoustic differences. Underlay type 3 was relatively stiff and exhibits the worst results regarding the absorption (0.1 at 2000Hz). Underlay type 2 in the wrong orientation (white side up) exhibits the highest alpha values (0.5 at 2000Hz), but the manufacturer’s recommendation is that the black side is up, so the absorption coefficient is reduced to 0.3 at 2000Hz. In combination with the later selected carpet type 2, the orientation of the underlay type 2 was not important for the very good results (0.8 at 2000Hz), therefore the black side up position has been selected.

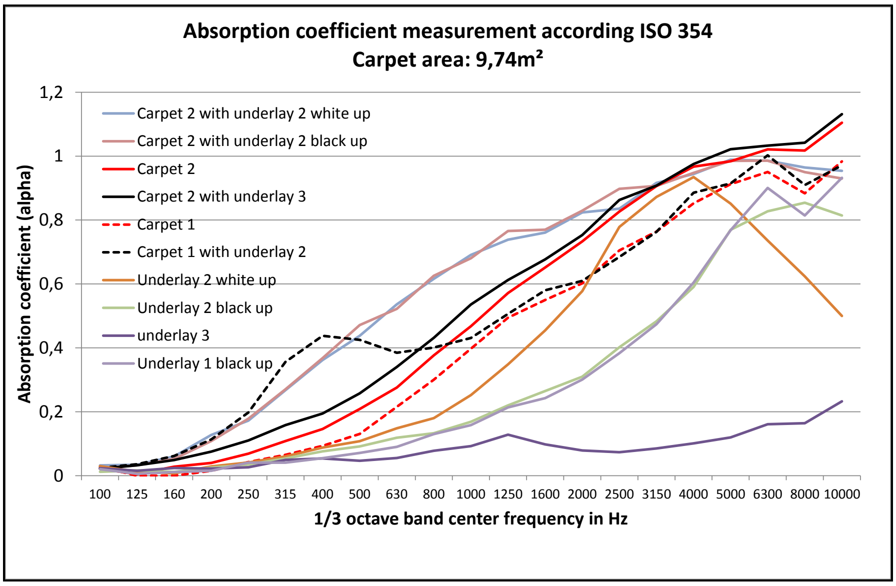


Figure 5 Acoustic comparisons of different types of carpet with different underlays

The previous paragraphs explain, how important the selection of the right carpet in combination with the used underlay is. Measurements of the carpet-underlay assemblies are crucial for the right decision to be made.

The authors investigated in this context another important issue, which is the resulting absorption capacity of different combinations of carpet with the human bodies if the worshippers standing or sitting on it. Figure 6 shows the results for 14 persons in different positions on the same carpet type 1 over underlay type 2.

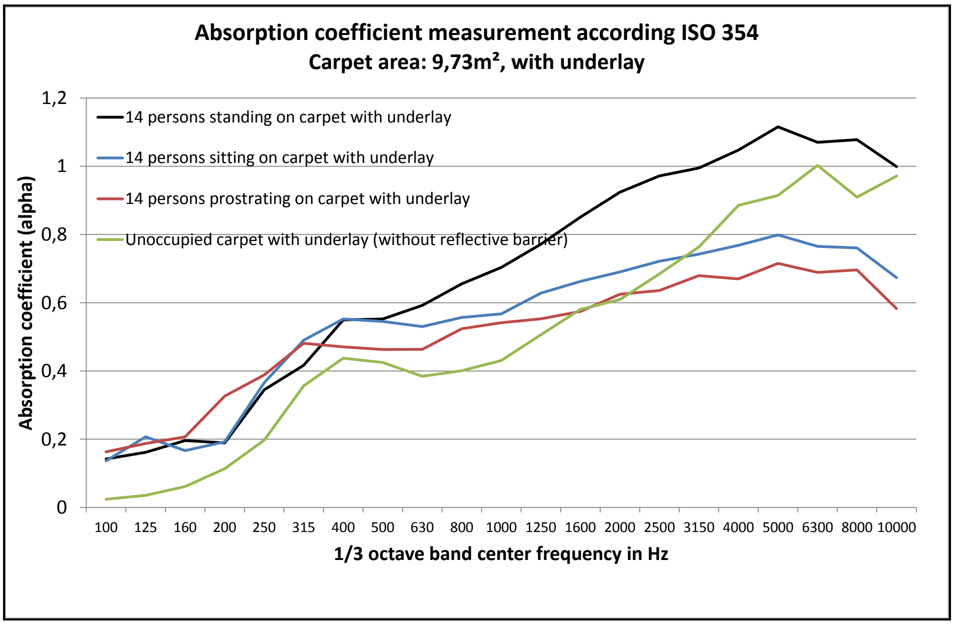


Figure 6 Absorption coefficients with persons on carpet type 1 over underlay type 2

It is shown that standing worshippers on carpet result in the highest absorption capacity compared to the other positions. In case of sitting or prostrating, the absorption at high frequencies is even reduced, as the highly absorbing surface of the carpet at these frequencies is hidden under the human bodies of the worshippers. Other different absorption coefficients result in case that the worshippers are standing or sitting on marble and not on carpet. This has been measured too.

4.2 Existing mosques under reconstruction

As in historical mosques (see above), the primary structure in existing mosques under reconstruction cannot be changed, i.e. volume, shape and the dimensions of the mosques are kept unchanged under reconstruction. Therefore, only the so-called secondary structure may be treated.

In contrast to the case of monument protection, the floors as well as other wall and ceiling surfaces may be considered for acoustical treatment with absorbers to reduce the reverberation in the mosque.

The room acoustic design for a mosque in the Middle East is used as an example of such kind of treatment. The primary structure of the mosque could not be influenced, so only the secondary structure was adapted in the design process.

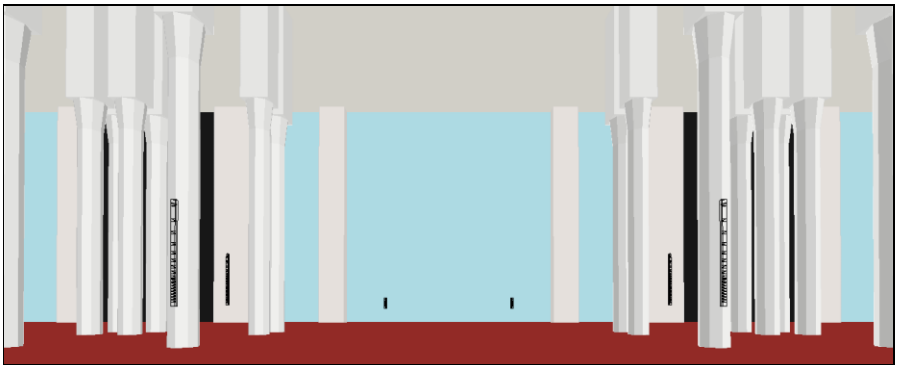


Figure 7 View into the model of the mosque

Due to the large room volume (almost 200.000m^3) and the lack of sound absorbing materials after proceeding with the design, the estimated reverberation time exceeded the recommended optimum range by far, Figure 8.

The effect of the large carpet-covered areas is taken into account in the green curve of Figure 8, which is basically reducing the reverberation time only at high frequencies.

Since the very long reverberation time in the speech frequency range could have still drastically degraded the intelligibility in this mosque, it had been indispensable to introduce acoustical treatment of some other areas, which can bring the reverberation time in the low- and mid-frequency ranges down to acceptable levels.

After several coordination meetings with the architects, it was possible to define, in addition to our acoustical requirement, their other major requirements/concerns as follows;

1. The treatment may not dramatically change the aesthetics of the mosque interior;
2. The treatment shall meet the requirements of other trades, such as stability, safety, fire-protection, durability, maintainability, etc.
3. The treatment shall be within the budget.

It was agreed that large areas of the *qibla* wall as well as the soffit of the mezzanine can be covered with special acoustical plaster, without changing the architectural impressions. Additionally the domes were agreed to be treated with seamless acoustic layers to avoid any sound focusing below them.

As mentioned, the already selected type of carpet in this case could not provide the sufficient absorption in the low- and mid-frequency ranges. Using a different type of underlay, the absorption behaviour of the carpet could have been improved and the amount of wall acoustical treatment could have been reduced.

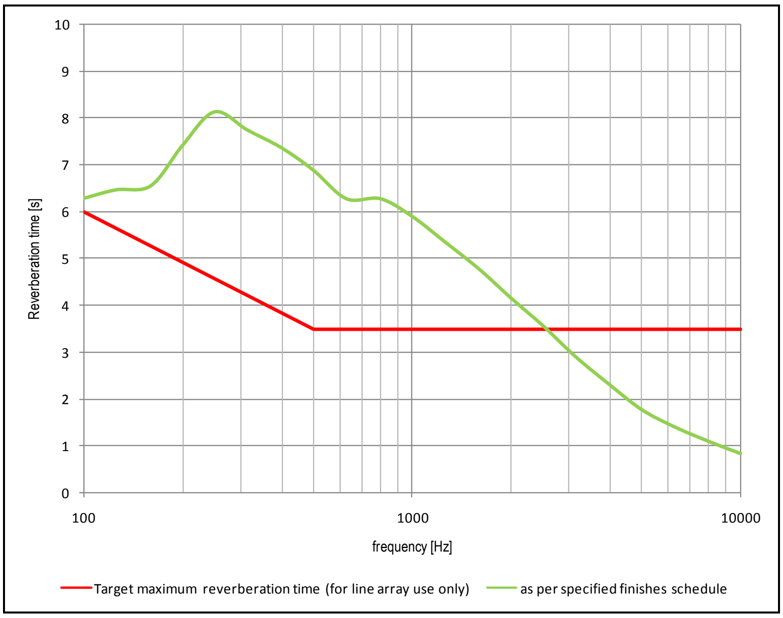


Figure 8 Reverberation time vs. frequency

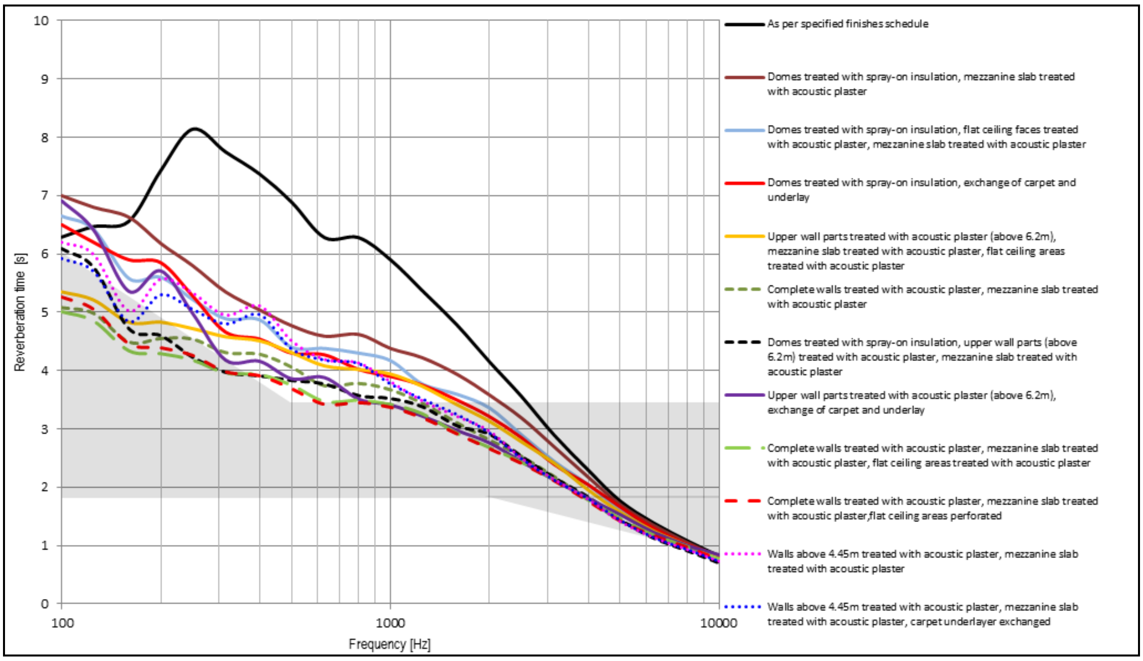


Figure 9 Effect of different treatment alternatives to reduce the reverberation time close to the tolerance range

4.3 New mosque construction

As mentioned under section 1, a mosque possesses normally the following architectural features:

- Carpet-covered floor
- *Qibla* wall
- *Minbar*
- Domes

With respect to acoustics, the influence of the floor carpet is normally positive and was discussed above.

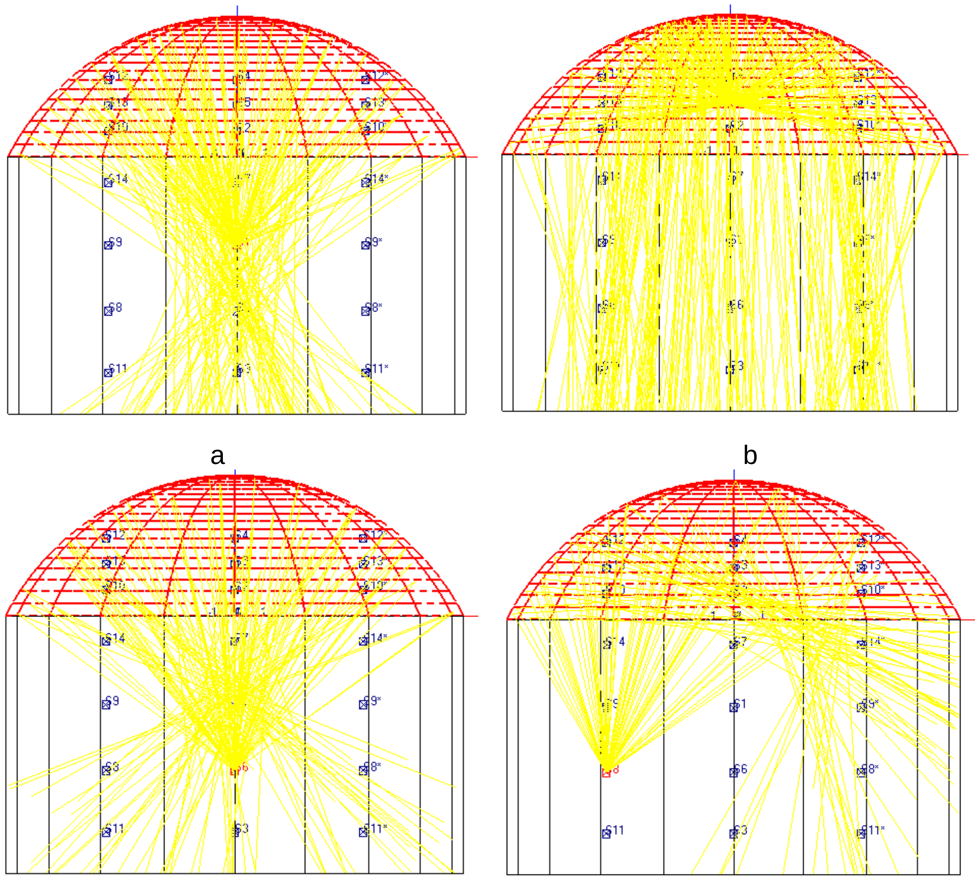
The worshippers, however, pray in rows (often marked on the carpet), hence they look to the q*ibla* wall, but they should perceive the *imam*'s speech coming from his spot. Any loudspeakers aimed to the congregation radiate sound directly to the rear wall and reflections thereoff might cause echoes. Therefore, the rear wall in new mosque constructions should be absorptive, i.e. covered with absorbers possibly concealed in ornamental structures. Generally, all parallel hard walls should be avoided.

Other wall surfaces may be also treated as much as needed to reduce the reverberation time to values below 4s at the midrange frequencies if possible, as discussed in the previous section.

One of the most problematic architectural elements from the acoustic point of view is the dome. Any concave surface has a focal point, at which it focuses the incident sound energy, which may result then in noticeable echoes. So, when designing a new mosque the size and position of domes have to be carefully considered. Figure 10a to Figure 10d show some sound focusing effects under domes.

When designing domes in mosques, these focusing effects must be investigated in advance. As seen in Figure 10a, the center point of a dome segment must be above the worshippers' ear level (small dome radius) or below the floor level (large dome radius, i.e. only little curved dome shape). This must be checked by computer simulation.

So in considering the above-mentioned design issues, echoes and excessive reverberation can be minimized, which is the basis for good speech intelligibility. But depending on the size of a mosque, it remains understandable that high speech intelligibility can only managed by a well-designed sound system.



c d

Figure 10 (a to d) Different radiation pattern caused by different source position below a dome: a) source in dome center point, b) source in dome focal point, c) source 5m above floor level d) same source height as in c, but 4m off-axis

5 SOUND SYSTEMS IN MOSQUES

The job of a sound system in a mosque is supplying as loud as needed direct sound and avoiding the excitation of a reverberant field. In the past, it was tried to realize this with a multitude of so-called simple loudspeaker units attached to existing construction pillars in the mosque. Light grids have been used in mosques as well to install the small loudspeaker boxes,

Figure 2 and Figure 3. These used boxes are point sources, i.e. they radiate the sound not only in the direction of the praying worshippers, but also in all directions of the mosque. At one spot these boxes create direct sound but on all other directions reverberant sound. This will degrade the intelligibility at the other places, not determined for coverage by that specific box. This method showed good results only by installing loudspeaker boxes in very short distances to each other, i.e. shorter than 5m, thus the supplied direct sound exceeds the diffuse sound components.

Nowadays, line arrays, i.e. electronically steered sound columns, are used in mosques. This kind of sound sources show highly directed sound radiation patterns and they are offered now by different manufactures.

The next Figure 11 compares the sound radiation balloon of a point source loudspeaker with such a line array.

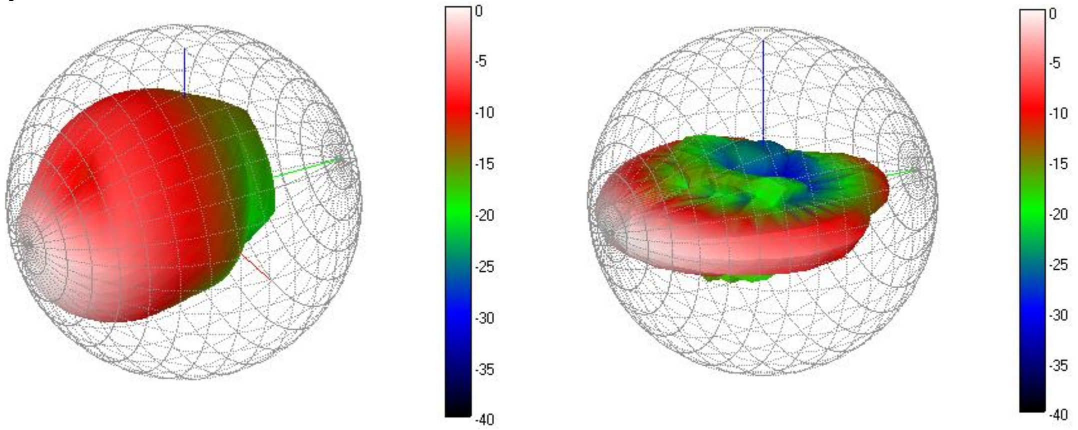


Figure 11 Balloons of a point source (left) and a steered line array (right), both at 1000Hz

The use of such electronically steered line arrays has significantly improved the intelligibility in mosques. This shall be shown by means of a computer simulation for *Sheikh Zayed Grand Mosque* in Abu Dhabi. The next Figure 12 shows the model of the mosque.

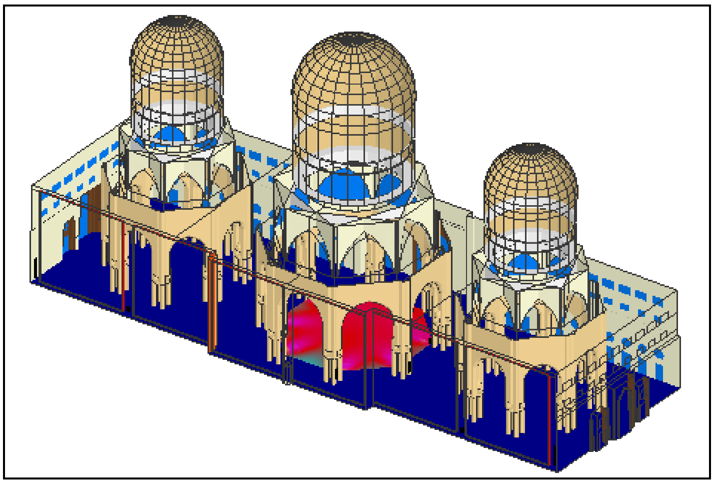


Figure 12 Model of the mosque

For the central part (around 800m^2, shown in red) the authors carried out a comparison between the use of two slim line arrays to the use of 6 distributed compact loudspeaker units, see next Figure 13.

In this comparison, the authors neglected the influence of noise and masking to demonstrate the acoustic impact on the results. With the two arrays, a smooth coverage over the depth of 40m can be observed, but with the six loudspeakers the coverage has the fingerprint of the arrangement of the loudspeakers. The average STI values (minus standard deviation) drop from 0.753 to 0.645. By adding the noise and masking influence it drops below 0.50 in the latter case.

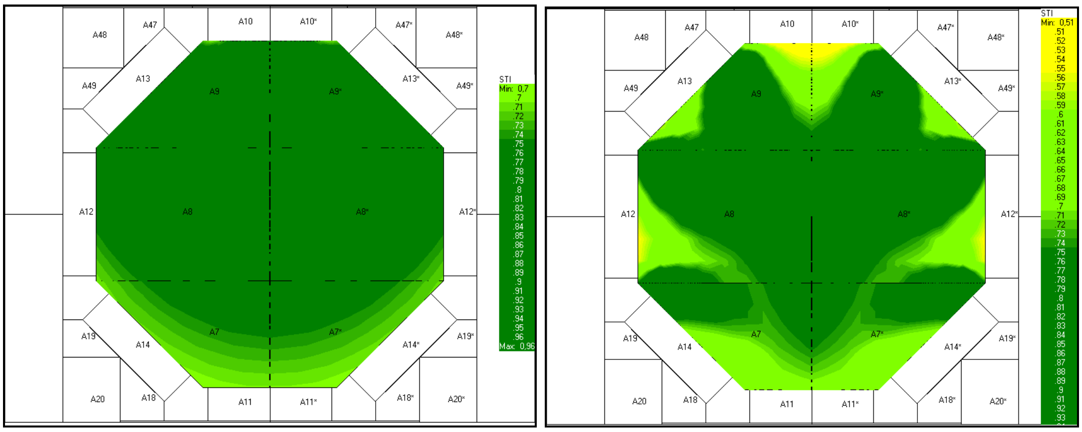


Figure 13 STI distribution with two line arrays (left) and with 6 compact loudspeakers (right) in the same area of a mosque

Interesting is the interaction between line arrays in reverberant spaces. In another mosque (reverberation time almost 10sec) one line array is used to cover the main area below a huge dome; the depth of this area was around 60m. Figure 14 shows the results with only one array.

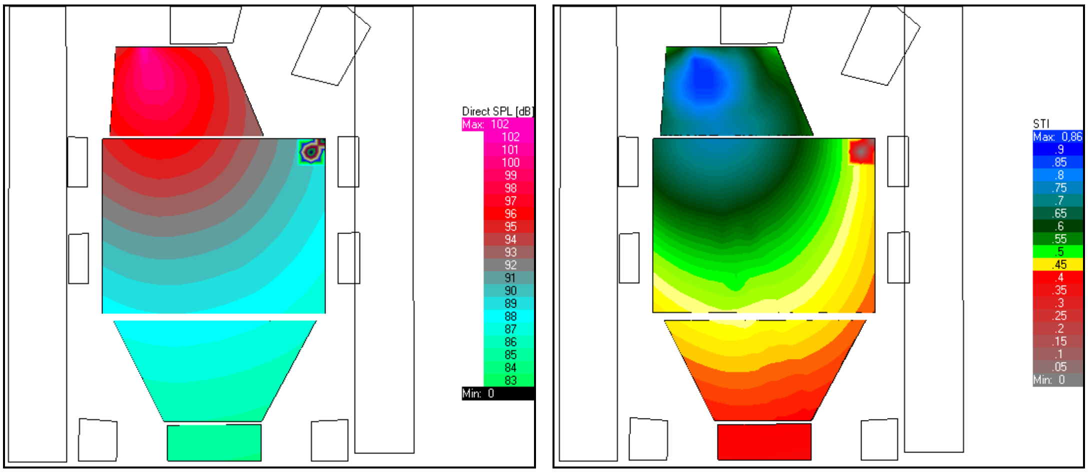


Figure 14 Sound coverage (left) and Intelligibility STI (right) in the main hall of the mosque

By employing a second delayed line array to improve the situation in the more distant spots, the following results are achieved, Figure 15.

As visible in Figure 15, the more distributed arrays don’t help to improve the coverage and the intelligibility results. The second array supplies direct sound to the more distant area, but also reverberant sound through backward radiation and room reflections to the front areas. So results are becoming even worse. Under such circumstances, it helps only to use a more powerful line array as the main one to cover with enough direct sound also the more distant areas in the mosque.

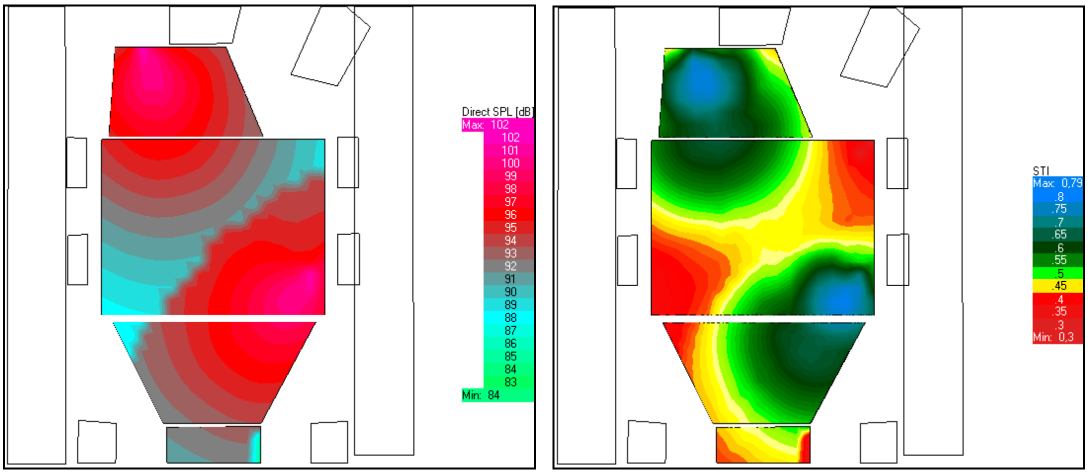


Figure 15 Sound coverage (left) and Intelligibility STI (right) with a main and a delayed line array

One of the important features of sound systems in mosques, which is one of the least taken care of as well, is the fact that the audience has three **ear levels**; none of them is the usual 1.22m AFFL normally adopted for seated persons.

The first ear level is the standing position, which can be taken 1.65m on average. The second is the kneeling/sitting position, which can be taken 0.8m, and the last is the prostrating position, where the prayer bows down with his/her forehead on the ground.

From the perspective of the sound system, the third position is of a little significance, as in this position the congregation members are normally listening to few narrations of the *imam* that they know in advance as a standard part of the prayer. That is why; one can assume that there are basically two ear levels, the standing and the kneeling/sitting positions.
Under harsh acoustical conditions, line arrays might become a necessity and the question is; which ear level should be considered for setting the beams of the arrays? There are three possibilities to consider;

1. The arrays can be set up to have a beam, or more, to comprise both ear levels, which means that the arrays shall inevitably send energy at any given time in directions, where energy is not needed. This can more or less nullify the advantage of the arrays in the reverberant space.
2. The arrays can be set up to have a beam, or more, to cover optimally a level, which is an average height of the two levels. With the vertically narrow beams of line arrays, this normally results in radiation patterns, which are optimized for neither standing position nor kneeling/sitting position.
3. The arrays can be set up to have a beam, or more, to cover optimally only one ear level not both, but which one is more important? The problem is that both ear levels are important, but it is still correct that the arrays need to be setup to optimally cover one ear level at a time. This is something that can be easily programmed in the arrays as presets for standing and kneeling/sitting positions.

The authors believe that a good design, and operation practice, is that the arrays are optimized for each ear level separately, and then the respective beam settings are recalled according to the prevailing ear level in any given long session. In this regard, the authors understand that Friday prayers with the weekly sermon shall dictate the settings of the kneeling/sitting position on Fridays, while the standing position beam settings shall be the more suitable choice for the so-called *Tarawih* prayers in the *Holy Month of Ramadan*.

The advantages of considering the right settings for the right ear level should not be underestimated, especially in acoustically challenging environments, where designers run after each single STI point.

6 SUMMARY

Like in every building, so also in mosques, the improvement of speech intelligibility cannot be achieved with sound systems alone without considering the room acoustic situation. Therefore certain design steps should be considered. In existing mosques in any case the design work should be starting with room acoustic measurements to understand the acoustic behavior of the space. In case of high reverberation the reason for that must be investigated and measures should be proposed to reduce the excessive reverberation. This may start with a new carpet, but especially with a new underlay. If this is not possible together with the client and/or the architect wall and ceiling areas should be determined for acoustic treatment.

The most difficult job is encountered in monument-protected mosques. In this case, only the carpet might be an option for changes for better treatment. If this is also not doable, then only a sophisticated sound system will help to improve the speech intelligibility there. In that case, a computer simulation is extremely important to check the quality of different sound system proposals. The belief that a solution, which is successful in one mosque, can be copied into a new one under design/construction may lead to a disaster. The selected topics highlighted in this paper can help designers follow the right steps towards increasing the speech intelligibility in mosques.

7 LITERATURE

/1/ Khaiyat, Sami A.: Acoustics of Mosques: An overview of current design Practice in Saudi Arabia, JASA, Third Joint meeting ASA-ASJ, Hawaii, December 1996

/2/ Karabiber, Z. G.: Acoustical problems in mosques: A case study on the three mosques in Istanbul, Forum Acusticum, Berlin 1999

/3/ Orfali, Wasim: Using DSP Controlled Electro-Acoustic Devices in Analysis, Simulation and Optimisation of Acoustics in Mosques, PhD 2007, Technical University Berlin, Germany