Sound Quality in Digital Meetings

Authors: Birger Schneider, Clément Laroche, Torben Christiansen, Tore Stegenborg-Andersen,

Introduction

In recent years, digital meetings have made strong inroads in how we communicate with each other. Not least the Covid-19 pandemic spearheaded widespread use of digital meetings. Meetings in companies – and between companies, sales activities, school activities, communication in administrations, governments and between governments, even at family level, etc. have been undergoing radical changes. Here video meetings have captured a substantial share of our way of remote communication - and at a rate of change, we hardly would have imagined just a few years ago.

Digital means of communication like digital meetings have strong upsides such as significant savings of resources, time, and improved efficiency in general. Further, it enhances decision making, catalyzing the improved agility in a globalized world. However, noticeable downsides exist such as elements of social isolation, difficulty in integrating people in workspaces, increase in stress, fatigue, tiredness, etc.

Digital meetings are instrumental in preserving and advancing digital transformation of society and at the same time supporting a strong green agenda by saving on resources (time, less travel, speed in decision making, etc.) in addition to increasing efficiency.

Although frequently known as video meetings, most of the information shared in digital meetings is through its sound content – not in visual artifacts. Hence, quality of sound is highly essential in digital meetings and contributes significantly to the success of a meeting – or if poor, to lack of efficient communication.

Background

Sound quality in digital meetings, not least good sound quality, depends on a variety of factors. Technological improvements pave the way for improved sound quality, and many enterprises have a stake in ensuring good sound quality – not least several Danish companies. However, to obtain high sound quality in digital meetings it is essential to understand the associated complexity - from recording of sound to play back of sound, including the entire chain of elements, equipment, algorithms, surrounding conditions and more. No single element can on its own right ensure high quality of sound in digital meetings, but balanced solutions ensure efficient communication.

From a sound perspective, the chain of communication can be separated into three main phases:

1. Recording: Equipment, algorithms incl. echo cancellation, acoustic environment.
2. Transmit: Solutions, algorithms facilitating optimal transmission
3. Play back: Equipment, algorithms, acoustic environment

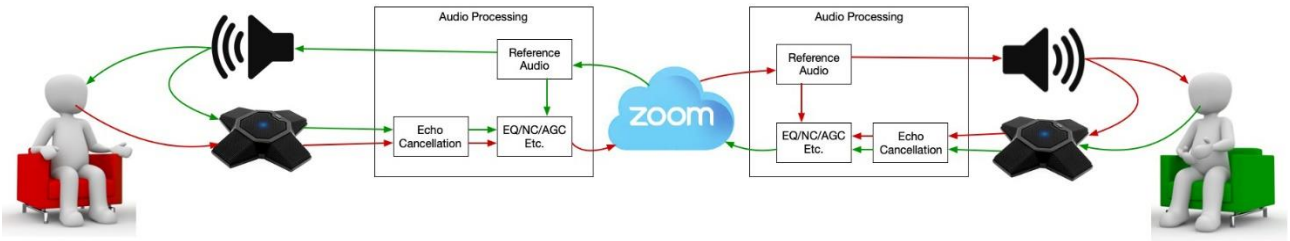

Figure 1: Illustration of the major elements in ensuring audio communication between two persons in conference call. Courtesy Zoom

In the recording phase 1), equipment such as quality microphones, offering sufficient direction sensitivity, optimal signal processing to separate signal and background noise, etc. are essential factors. A headset with a boom-arm microphone promises better performance than a microphone in an earbud - up to 20 dB better performance. However, user convenience, market requirements and fashion to some degree, dictate a significant market for earbud usage. Hence, the technological challenges for suppliers of such equipment increase aiming to ensure good sound quality disregard physical constraints. Use of efficient algorithms, including advanced digital signal processing, artificial intelligence (AI), etc., may overcome some, or most of the downsides of using a challenging sound quality implementation such as an earbud, since market requirements really drive this ubiquitous communication platform.

Speaker phones is another popular solution for good sound quality in digital meetings. The solution includes both microphones (often several and direction sensitive) and loudspeakers integrated into one unit to ensure natural 'double talk' (simultaneous hear and speak like in natural conversation), **Ref. 1**. Technologically 'double talk' poses a challenge since interaction between microphones and loudspeaker in the unit must be suppressed. In addition, echo cancellation is of utmost importance. Digital signal processing helps suppress/cancel linear echo signals caused by audio waves travelling at multiple distances (varying delays), e.g. caused by people (sometimes even moving), walls, open laptop screens. Furthermore, non-linear components (loudspeaker and microphone distortion, mechanical resonance caused by underlying table, mechanical parts, vibrating wires and subassemblies, etc.) need to be suppressed using addition adaptive filters, etc. All in all, really complex solutions to ensure high sound quality.

Finally, many users may just rely on using built-in microphones and speakers in computers, tablets, and mobile phones, hence typically accepting poorer sound quality, when employing such solutions.

In transmission, 2), latency is an issue that influences quality of the sound in transmission. The total one-way latency for networked audio and video includes: The delay due to acquisition of audio and video data, data compression, channel coding, network latency, channel decoding, data decompression, packet loss concealment, echo and acoustic feedback cancellation, playback buffering, and actual playback of the audio and visualization of the video, see e.g. **Ref. 2**.

Another significant factor influencing the recording of sound is the acoustic environment, in which the recording/play-back takes place. A noisy metro station hardly promises an optimal environment for a good sound recording, and even in a quieter room, factors such as reverberation, i.e. echo, etc. may impose a significant impact on the quality of recorded sound. Adding to this is the fact that a user does not have feedback of the sound quality produced. If for example, a user employs a headset that singles out surrounding noise, then he or she tends to talk louder if no efficient side-tone assists[1], since isolation effects of the headset, in absence of an adequate sidetone, reduce the sound feedback to the speaking person.

Many have also experienced that set-up of communication channels for a digital meeting have been compromised due to various security consideration by IT staff in companies. As a result, the audio channel may appear poor, while the video channel offers good transmission, or opposite, or even poor performance for both video and audio channels.

The situation today

Transmission of sound is typically handled through systems like Teams (Microsoft), Zoom, Cisco WebEx, Google Meet or similar. These systems are highly optimized to ensure good quality in transmission. That is obtained through sophisticated algorithms where also the quality of the hardware used for recording plays a pivot role. Quality recording and play back solutions are typically certified to meet substantial requirements of the transmission solutions. For example, Microsoft has through its *'V4.0 Final Specification version to grant Certified for Teams'* a solution **Ref. 3**, where providers for professional markets of equipment such as headsets, speaker phones, earbuds, etc., should comply to a highly detailed set of specifications to get certified. In turn, that allows Microsoft to optimize the transmission. Hardware products that are not certified

[1] *Side tone is audio feedback from one's own voice, that a headset/headphones user hears when speaking into the microphone. The amount of sidetone on e.g. land-lines is typically 8%, and is 4% or less for cellular phones. Lacking adequate sidetone causes some people to shout or speak too loudly. Quality headsets have good control of side-tones.*

run a risk of reduced sound quality for their products, since the hardware will not be supported as well in transmission as those, who live up to the certification requirements.

However, it is worth noticing that certification is base upon lab test setups, using 4 speakers and a head and torso simulator. Certification is not based upon real world performance.

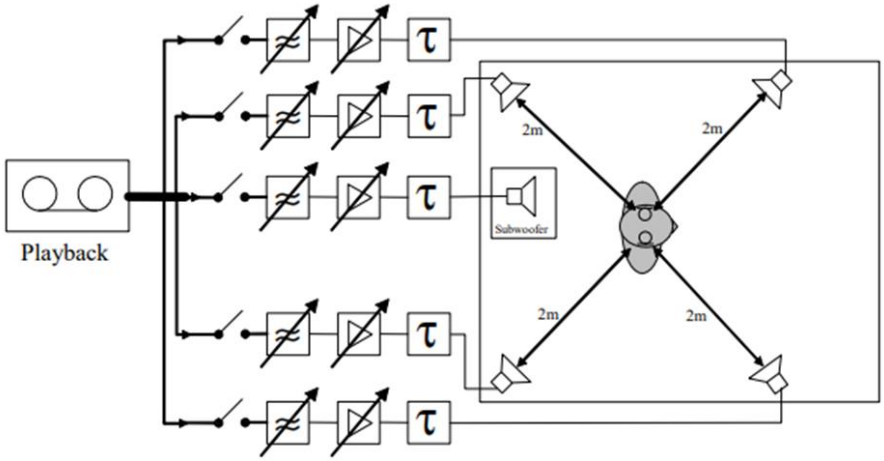

Figure 2: General setup for headsets in equalized four loudspeaker arrangement in an office room (ETSI EG 202 396-1 V1.2.2 (2008-09)

Microsoft requirements have been upgraded recently, see e.g. "USB audio and video devices certified for Microsoft Teams", Ref. 4.

Challenges related to perception of sound quality

An important fact of poor sound quality is that it imposes a higher cognitive load on the listener, Ref. 5 Ref. 6. A few words lost in a conversation makes the brain work harder to understand the meaning, thus requiring more cognitive resources. Our brains must interpret the audio signals that are registered by the sensors in our ears. It is a well-known observation by many people that the cognitive load of poor sound quality increases the fatigue of a listener significantly over time due to difficulty of listening, noise, and other annoying effects. Such effects typically lead to lack of concentration and may even result in stress for users active in digital meetings for longer times. People active in e.g. call-center duties, where they are on duty for longer periods in calls with customers, are known to have a high drop-out rate from jobs. The stress during such working conditions to some degree mirror the effects in digital meetings, when reduced sound quality adds to stress, although also other factors govern the stress level that callers in call centers are enduring. One source reports that 63% of people questioned admit lack of concentration and efficiency, if poor sound quality dominates, whereas 56% of employees believe good audio will prevent moments of stress at work, Ref. 7.

In addition to the echoing effects when using low quality headsets[2], the environment from which digital meetings are conducted, in turn also influences users' perception of sound quality. Reverberation[3] conditions of a room, background noise, etc. impact the perceived quality of sound, e.g. if meetings are taking place in rooms where colleagues are sitting nearby or noisy environments. For such situations, use of headsets or speakerphones with good noise isolation of surrounding noise is an obvious choice. If participation in a digital meeting takes place outside a room, the challenge of surrounding noise can be even more critical, e.g. if the participant in a digital meeting is driving in a car, sits in a coffee shop, walks in the street or is in other types of noisy environments. Use of high-quality headsets is then often a solution, although a drawback may be inconvenience of feeling/being acoustically isolated from the surroundings.

[2] *Echo effects are a result of proximity of the microphone to the speaker and present a challenge for headset manufacturers. The problem can be reduced by employing diligent attenuation. Low quality headsets typically suffer from poor attenuation of echo effects.*

[3] *Reverberation is persistence of sound, or echo after a sound or signal produced is reflected causing numerous reflections to build up and then decay as the sound is absorbed by the surfaces of the environment, typically a room.*

As already stated, the sound content of a digital meeting is normally the essential part of communication in a digital meeting. However, the poor synchronization of image and sound may lead to frustrations for the user. Such 'lip-sync' problems are well known since years in the broadcast industry and are known to reduce the uptake of information during a transmission event. The sensitivity of people to lip-sync varies significantly, but as a rule of thumb, variations in synchronization of more than 45 ms is sensed by most people - and some are sensitive even down to 15 ms, **Ref. 8 Ref. 9**. For transmission of music latency is even more challenging, and latency requirements for music are even tougher, as is variation in play back variations, see Ref. 10. In many audio applications, for example hearing aids and other types of equipment that people use for interaction, the latency requirements are even tougher, requiring max delays of 5 ms.

Although not directly an element of sound quality, the element of 'safe listening' somehow also raises a flag of concern. WHO and others are struggling to ensure that users of sound are not experiencing sound levels beyond safe limits for example as defined in ITU safe listing standards. Not only the level of sound but also the duration of exposure to sound are essential. In severe cases, acoustic shocks can even lead to PTSD.

Market situation

Danish companies hold a strong position in the global market of solutions of professional conference speaker phones, headsets, and hearables. A company like GN-Audio tables a turnover of 10,4 billion DKK for its 2021 fiscal year. Its brands, particular JABRA with headsets for professional use, speaker phones, and earbuds, now exceeds its long-time rival in the market, US based Poly (previous Plantronics).

Another strong Danish player in the market for professional headsets and speaker phones, even headsets for gaming is Demant owned EPOS. Holding a market position of 1,2 billion DKK/year is yet another impressive figure. EPOS also focus its products on mission critical applications in aviation communication.

B&O is renowned for its speaker phone Beosound A1, and its models of Beoplay headsets. Some of the latter offer noise cancellation. The B&O products are highly popular – not least for listening to music. Given that more people now work from home, B&O products carve into the fast-growing professional use market traditionally services by Jabra, EPOS and other.

Headsets products from other Danish manufacturers are also available, e.g. from DALI and AiAiAi. Although focused more on high quality music listening, such products also serve in use in digital meetings.

RTX offers a range of boom-arm headset products, wired solutions or wireless. Entry-level, mid-end, or high-end solutions, offering use of ANC (Active Noise Cancellation) and ENC (Environmental Noise Cancellation) ensure high perceived audio experience for the users

INVISIO, has established a strong market position as global leader in advanced communications and hearing protection systems for mission critical applications in noisy environments like military, public safety, and the likes. The company employs advanced bone conductor headsets as part of the application. Although not for use in classic digital meetings, the importance of such communication units for severe noise situations is underlined by the company's success in servicing markets in the USA, UK, Canada, Australia, Denmark, and other countries ending up with sales of 352 million DKK for its 2020 business of headsets and communications systems. Since then, the company has also acquired Racal Acoustics, a world player in headsets for military use.

Start-up companies are mushrooming in the market. AceZone headsets are serving a gaming market rather than a market for digital meetings, but still a market for high quality headsets. Even players employing alternative technologies like bone conductor solutions emerge, e.g. startup company Auricle that was recently spun-off from DTU. Other startup companies are busy in proving software solution for improving sound quality. Such solutions aim at being integrated with OEM suppliers or in systems solutions. IDUN Audio focuses on delivering software that can be configured for enhancing many different everyday use cases to obtain a more natural audio environment through Dynamic Spatial Audio. Similarly Augmentedhearing.io focuses on improving the sound, not least the speech quality, captured by a microphone and through use of AI techniques.

The Danish market for headsets is also a market for sub suppliers. The importance of a local support industry is well known and local subcontractors in the audio industry are no exception. High quality headsets for

example require access to the best test solutions. HBK, Hottinger Brüel & Kjær with is professional line of measurement microphones, Heads and Torso Simulator (HATS) and measurements accessories, and G.R.A.S. with similar products for acoustical testing are world leaders in these segments. Their closeness and inspiration to manufacturers of headsets, speaker phones, earbud, hearing aids, etc. are certainly of importance to grow the Danish industries in these sectors.

A component supplier like Sonion, supplier of microminiaturized components for hearables including hearing aids, earbuds, etc., is a global leader in designing and manufacturing components and solutions for hearing instruments to improve people's quality of life. Ole Wolf with its high-quality speakers, receivers, microphones and buzzers - and unique design capabilities is yet another important player in the Danish sub supplier market for audio products.

Finally, it is worth to notice that the strong market position of Danish industry in this market segment to a large extend also is a result of significant R&D at several Danish knowledge institutions, e.g. universities like DTU and AAU, FORCE Technology (GTS institute), but also to some degree at Sonic College, 'Den Danske Filmskole' (National Film School of Denmark), and others.

Expected future developments in the market

Technology driven developments in the market for digital meetings are likely to continue in coming years- and even accelerate due to progress happing in related technology areas. Digital video meetings will see video improvement to HD quality, screen sharing with high framerates and basically no lagging with audio. Good and improved sound quality in that context is no exception. Zoom already support stereo and stereo is likely to be commonplace in digital meetings in the coming years.

Improvements in digital signal processing in background noise suppression technology to handle current shortcomings in relation to equipment and acoustic environments will inevitably see light in future solutions of headsets, speakerphones, earbuds, and other audio related solutions.

AI has already started to make inroads in solutions allowing systems to be trained to yield even better signal isolation and optimization, e.g. by allowing a solution to be optimized for specific environments, languages, and others. A much higher level of sophistication is likely to emerge in the domain of augmented hearing.

As hardware accelerators for AI are getting smaller, more efficient and requiring less power, we may even one day expect to see solutions in e.g. headsets, where simultaneous translation of language can be facilitated. Many other dreams of today are likely to emerge in the market in coming years.

For example, processing power and memory is increasing at a fast rate and is taking headset to a new level of performance, where even links to computers and mobile phones are no longer required. Headsets equipped with immersive computational power, low power performance, and many sensors, e.g. gyro sensors, will facilitate high performance audio performance supported by additional AI for sophistication of quality of speech even as standalone solutions, may be even for dynamic spatial applications, and no need to support from computers or mobile phones. EPOS already in 2020 launched its Adapt 660 AI headset, the world's first headset employing AI, machine learning, to maximize voice clarity by enabling the headset to adapt to speech while studying the surrounding sound environment, see Ref. 11. The built-in neural network aims at improving sound quality.

Communication systems for digital meetings today by and large only offer mono audio signals support. Basically inconvenient for meetings, where several persons participate, since all voices are mixed into a single channel, which frequently makes understanding more difficult and certainly is unnatural. Spatial sound[4] technology is gradually emerging in entertainment systems. Apple already support spatial audio in Apple AirPods using Dolby Atmos, Samsung in its Galaxy Buds Pro, offers '360 audio' solutions very similar to Apple's spatial audio, etc. Digital filters support soundtracks of movies and TV-shows to appear almost like individual sound sources originating from consistent points within a scene, whether it's off to one side, behind you, above you or below you. The spatial sound solutions even in some implementations

[4] *Spatial sound is simulated 3D audio, yielding enhanced audio experience where you can perceive sounds from all directions. Leading spatial sound softwares today include Windows Sonic, Dolby Atmos, and DTS.*

follows the position of one's head. In consumer audio, industry is moving towards 22.2 channel support, Ref. 12.

It is envisaged that spatial sound may migrate into use in digital meetings when communication systems over time expand to support multichannel sound.

For several Danish players in the sound industry segment, it offers significant opportunities to grow the business segment of quality audio solutions for digital meeting applications. Although the business segment still is limited for new technology solutions, long term opportunities promise well. Those, who dare risk entering new market solutions in a promising technology have a higher chance of success than those, who wait, until a given technology has proved its market value. When markets become too mature, it is difficult for Danish companies to enter and take fair market shares. However, as with other industrial sectors, technology on its own right does not ensure success, but garnered with strong sales initiatives, marketing creativity, financial muscles, logistics, and others, the opportunity certainly is there and is likely to lead to success, given current Danish traditions in the market segment of audio.

An important prerequisite is that strong R&D environments remain in Denmark in the sector of audio solutions. Increase in R&D at universities and other knowledge institutions, and not least in industry, supported by strong innovation and agility in adapting to market needs and opportunities must prevail. Here people play an import role. A stronger uptake of students at universities and profession schools is a must to ensure that current strong players in the audio industry remain in Denmark – and that new startups emerges. The STEM disciplines (science, technology, engineering, and mathematics) are currently suffering in general in relation to obtaining the necessary share of each generation of young people taking a higher education – not least in comparison to many of the countries we compete against worldwide. Audio education including fast increase in supplementary disciplines such as signal processing, AI, big data, IoT, etc. are becoming the reality of success – also for sound quality in digital meetings.

Recommendations for Danish R&D activities

The market for headsets to offices, call centers and industry is a highly professional market – and hence face extended requirements. Customers usually demand certified products. Complying to 'de facto' standards such as Microsoft (for 'Teams'), 'Zoom' and similar, and even ETSI EG 202 396-1 and ETSI TS 103 106 have become almost mandatory as a minimum level of performance e.g. for the sound quality to ensure optimum performance in digital meetings.

However, on its own right that is no guarantee of good quality of speech under a variety of usage conditions. Firstly, the standards and "de facto" standards focus on speech quality. Secondly, extended use of tablets and laptops have moved many digital meetings out of controlled environments in offices to cafés, cars, pubs, cafeterias, call centers, even train station, crossroads, and other traffic situations.

Standard test conditions for certification according to standards and 'de facto' standards are based upon laboratory test conditions (e.g. using robot tests like HATS) is not sufficient to guarantee high performance sound under many real-world usage conditions. One simple example, where a certified product is no guarantee of good sound quality, is usage under windy conditions. Wind noise, sometimes a reality in real-world digital meetings, is not part of the requirements for certification for headsets today. Similarly, optimum performance under other 'real world' usage conditions may fall short if a headset 'only' meets the requirements of the 'de facto' and/or full standards. Use conditions in digital meetings are increasingly becoming more and more disperse.

In the professional market segment it is a known fact that many lower-cost products fail to perform well under certain typical usage situations – even though products are certified and comply to standards and 'de facto' requirements.

For a professional supplier industry of headsets, conference speakers, earpieces and the likes, the ability to master usage under real-world conditions is essential. Given that presents standards and "de facto" requirements are inadequate, R&D into higher levels of requirements beyond today's more basic levels of requirements become important and instrumental in assisting Danish sound companies in carving further into this market. Not only for the larger manufacturers of products - not forgetting new players and start-ups - but certainly also to suppliers of subset solutions and modules in microphones, speakers, algorithms, general

software tools, mechanical assemblies, etc. play an important role in the conquest of the market. Even chip designers serve an essential role due to the ever-increasing demands for miniaturizing in wearable products.

A challenge also exists in relation to limitations of existing test technologies to new applications areas. A prerequisite for e.g. 'Teams certification' is the use of a test robot like HATS, basically a puppy for use under test. However, the approach of using HATS is unsuited for e.g. bone conductor headset applications. Hence, the current test technology limits the use of bone conductor solutions for the professional market of certified headsets. Bone conductor-based headsets could very well offer strong solutions for certain market segments in professional digital meeting contexts. For such product to obtain certification, we need new test techniques.

In bridging the gap between the lab and the real-world, new efficient simulation capabilities are needed to ensure the Danish industry to stay in the forefront of the market. Hence, access to significant datasets to help in e.g. AI optimizations appears essential. One focus area could be adaptive hearing support for a working force that now have to stay longer in the workplace due to demographic changes. Aging effects in listening make it more difficult for many older people to obtain full benefit of efficiency of digital meetings. To ensure this group of people benefiting fully in the use of digital meetings, solutions may have to be optimized also for this user community. Data is needed to establish a better development strategy for systems solutions. Collaboration in data collection for specific user groups, here persons with reduced hearing abilities, make sense, e.g. in collaborative project between companies, universities, and GTS institutes.

Many Danish companies in this market segment have an incentive to further enhance solutions, and Danish R&D activities at universities and other knowledge institutions have strong traditions to build on in the focus area.

Joint R&D activities between knowledge institutions and industry, small as well as large companies, including also B2B collaboration, should form value chains from innovation to markets and should focus on e.g.

1. ***Realistic future requirements for headsets:***
   Additional requirements over and above current standards/'de factor' standard requirement and associated test solutions.
2. ***Evaluation methods and simulation solutions:***
   Bridge lab test requirements more realistically to real world usage and more sophisticated lab equipment, e.g. test solutions for professional bone conductor product certification.
3. ***Data collection of high-quality sound data and simulation of data:***
   Data collection project, and e.g. also R&D access to hearing related public health data.
4. ***Machine learning:***
   R&D in High quality data, Metrics of objectively parameterize neural network.
5. ***Augmented hearing:***
   Extended use of AI in systems, advanced signal processing, including efficient algorithms to handle real-world usage conditions and overcoming challenges caused e.g. by the surrounding environment.
6. ***Research in edge processing:***
   Including architecture tuning, even best practices in use of emerging chipsets for advanced audio applications. Today a growing number of suppliers are active in this segment, e.g. chipsets from Qualcomm, Edge Impulse, Green Waves, etc., but no Danish developed chipsets yet.
7. ***Perceptual evaluation of combined audio and video applications:***
   As employed in digital meeting solutions.
8. ***Headsets and conferencing systems:***
   Robust Own Voice pickup (microphone) adapting to any environment
9. ***Audio environments ("physical rooms"):***
   Studies, recommendations, development of design strategies and measurement solutions for improving audio environments for digital meetings.
10. ***Transducer hardware improvements:***
    E.g. reduced non-linear performance of speakers and microphones.

11. ***Solutions for miniaturized electronics:***
    Supporting low power features for wearable products and solutions, e.g. microelectronics, ear-eeg, etc.
12. ***Material research in sustainable materials for speakerphones:***
    High stiffness, high damping, thus reducing structural borne vibrations outside of audio range.

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The authors would like to thank individuals and companies that have been instrumental in reviewing, supporting, and providing background material for this ‘guiding star’ note.

It is our hope that the paper can serve as inspiration for more R&D in the relevant focus areas and domains and be used as a reference in applications for R&D activities.

We intend to update the paper as more feedbacks are received.

Danish Sound Cluster

Danish Sound Cluster (DSC) is an organization covering the whole sound industry in Denmark. We support innovation in sound and ensure that knowledge, research and competencies find their way into companies and products. In addition, we focus on collaboration between companies as well as between companies and knowledge institutions (universities, GTS institutes, etc.)

DSC is supported by industry, its members, Danish Agency for Higher Education and Science, and Danish Board of Business Development.

DSC has its headquarters in Struer, Denmark and also offices in Hoersholm and Copenhagen, Denmark. Information about DSC can be found a www.danishsound.org

References

Ref. 1: *"Superior Double Talk Performance & Echo Cancellation"*
EPOS: Expand 80 Series

Ref. 2: *"Low Delay Robust Audio Coding by Noise Shaping, Fractional Sampling, and Source Prediction"*
Jan Østergaard, Aalborg University
2021 Data Compression Conference (DCC), pages 273-282

Ref. 3: *"Microsoft Teams Video Capture Specification*
For personal and conferencing devices"
V4 April 2019, Microsoft Corporation
https://docs.microsoft.com/en-us/skypeforbusiness/certification/test-spec

Ref. 4: *"USB audio and video devices certified for Microsoft Teams"*
6 February 2022
https://docs.microsoft.com/en-us/microsoftteams/devices/usb-devices

Ref. 5: *"Technological Factors Influencing Videoconferencing and ZOOM Fatigue Ref. 4"*
Alexander Raake, Kathrin Schoenenberg, Markus Fiedler, Katrien de Moor, Nicola Döring
arXiv: 2202.01740v1
February 4, 2022

Ref. 6: *"Listening Effort: How the Cognitive Consequences of Acoustic Challenge Are Reflected in Brain and Behavior"*
Jonathan E. Peelle
Ear & Hearing, 2017
the American Auditory Society, by Wolters Kluwer Health, Inc.

Ref. 7: *"Meeting Rooms"*
EPOS
https://www.eposaudio.com/en/dk/enterprise/meeting-rooms

Ref. 8: *"Relative Timing of Sound and Vision for Broadcast Operations"*
ATSC Implementation Subcommittee Finding
Advanced Television Systems Committee
Doc. IS-191¸ 26 June 2003

Ref. 9: *"The relative timing of the sound and vision components of a television signal"*
EBU Recommendation R37-2007
Geneva, February 2007

Ref. 10: *"Low Delay Robust Audio Coding by Noise Shaping, Fractional Sampling, and Source Prediction"*
Jan Østergaard, Aalborg University,
2021 Data Compression Conference (DCC, page 272 to 275

Ref. 11: *"EPOS ADAPT 660 rated one of the best products in it's range by Frost & Sullivan"*
Frost & Sullivan, May 30, 2021
https://www.eposaudio.com/en/dk/enterprise/insights/white-papers/adapt-660---frost-and-sullivan-review

Ref. 12: *"Object based audio: Opportunities for Improved Listening Experience and Increased Listener Involvement"*
Robert Bleidt, Arne Borsum, Harald Fuchs, S. Merrill Weiss
https://www.iis.fraunhofer.de/content/dam/iis/en/doc/ame/Conference-Paper/BleidtR_SMPTE2014_Object-Based_Audio.pdf