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| Technical Report | |
| 3rd Generation Partnership Project;  Technical Specification Group Services and System Aspects;  Study on Diverse Audio Capturing system (Release 19) | |
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# Foreword

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In the present document, modal verbs have the following meanings:

**shall** indicates a mandatory requirement to do something

**shall not** indicates an interdiction (prohibition) to do something

The constructions "shall" and "shall not" are confined to the context of normative provisions, and do not appear in Technical Reports.

The constructions "must" and "must not" are not used as substitutes for "shall" and "shall not". Their use is avoided insofar as possible, and they are not used in a normative context except in a direct citation from an external, referenced, non-3GPP document, or so as to maintain continuity of style when extending or modifying the provisions of such a referenced document.

**should** indicates a recommendation to do something

**should not** indicates a recommendation not to do something

**may** indicates permission to do something

**need not** indicates permission not to do something

The construction "may not" is ambiguous and is not used in normative elements. The unambiguous constructions "might not" or "shall not" are used instead, depending upon the meaning intended.

**can** indicates that something is possible

**cannot** indicates that something is impossible

The constructions "can" and "cannot" are not substitutes for "may" and "need not".

**will** indicates that something is certain or expected to happen as a result of action taken by an agency the behaviour of which is outside the scope of the present document

**will not** indicates that something is certain or expected not to happen as a result of action taken by an agency the behaviour of which is outside the scope of the present document

**might** indicates a likelihood that something will happen as a result of action taken by some agency the behaviour of which is outside the scope of the present document

**might not** indicates a likelihood that something will not happen as a result of action taken by some agency the behaviour of which is outside the scope of the present document

In addition:

**is** (or any other verb in the indicative mood) indicates a statement of fact

**is not** (or any other negative verb in the indicative mood) indicates a statement of fact

The constructions "is" and "is not" do not indicate requirements.

# Introduction

Providing immersive voice and audio services by end-user devices is becoming more and more practicable with the development of 4G/5G technologies. Related requirements have been investigated in 3GPP TR 22.891. Several use cases for VR are envisioned in TR 26.918, and for these cases the corresponding audio capturing system are generally considered. As such, capturing capability is crucial for making truly immersive voice and audio experiences.

Due to physical constraints on their outline shapes and sizes, the end-user devices are usually configured with different numbers of microphones and also different microphone setup configurations, hence different audio capturing capabilities are expected. Based on this, the present document gives diverse audio capturing system.

# 1 Scope

The goal of the FS\_DaCED is to study diverse audio capturing methods and applicable audio formats for the end-user device considering the current physical and software constraints the scope of the work is shown in Figure 1-1.

A screenshot of a computer

Description automatically generated

**Figure 1‑1 Scope of FS\_DaCED**

This document addresses audio capturing configurations for end-user devices, which is to make the devices to have audio capturing capability in order to provide truly immersive voice and audio service.

This document aims to study the following aspects:

1) Factors of different UE categories related to audio capture.

2) Components used in audio capture.

3) Acoustic design for audio capture.

4) Signal processing, e.g., microphone array beamforming processing, AEC processing etc.

5) Example of audio capture processing solutions.

# 2 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication, edition number, version number, etc.) or non‑specific.

- For a specific reference, subsequent revisions do not apply.

- For a non-specific reference, the latest version applies. In the case of a reference to a 3GPP document (including a GSM document), a non-specific reference implicitly refers to the latest version of that document *in the same Release as the present document*.

[1] 3GPP TR 21.905: "Vocabulary for 3GPP Specifications".

[2] 3GPP TR 26.891: "5G enhanced mobile broadband; Media distribution".

[3] 3GPP TR 26.918: "Virtual Reality (VR) media services over 3GPP".

[4] 3GPP TS 26.119: "Media Capabilities for Augmented Reality".

[5] 3GPP TS 26.258: "Codec for Immersive Voice and Audio Services (IVAS); C code (floating point)"

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[7] Wittek, Haut, Keinath: “Double M/S – a Surround recording technique put to test”, 24. Tonmeistertagung 2006

[8] P. Geluso. “Capturing Height: The Addition of Z Microphones to Stereo and Surround Microphone Arrays,” presented at the 132nd Convention of the Audio Engineering Society (2012 Apr.), convention paper 8595.

[9] Fischer, C., Zingler, D., Medina Victoria, J.: “MS-3D: Extending the Double-MS Array for 3D-Audio applications” (29th Tonmeistertagung – VDT International Convention, November 2016)

[10] J. Benesty, D. R. Morgan and M. M. Sondhi, "A better understanding and an improved solution to the specific problems of stereophonic acoustic echo cancellation," in IEEE Transactions on Speech and Audio Processing, vol. 6, no. 2, pp. 156-165, March 1998.

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[14] C. D. Salvador, S. Sakamoto, J. Treviño, and Y. Suzuki, “Enhancement of spatial sound recordings by adding,” J. Inf. Hiding Multimedia Signal Process., vol. 8, no. 6, pp. 1392–1404, 2017.

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[18] 3GPP TS 26.258: "Codec for Immersive Voice and Audio Services (IVAS); Detailed Algorithmic Description including RTP payload format and SDP parameter definitions".

# 3 Definitions of terms, symbols and abbreviations

## 3.1 Terms

For the purposes of the present document, the terms given in 3GPP TR 21.905 [1] and the following apply. A term defined in the present document takes precedence over the definition of the same term, if any, in 3GPP TR 21.905 [1].

## 3.2 Symbols

Void

## 3.3 Abbreviations

For the purposes of the present document, the abbreviations given in 3GPP TR 21.905 [1] and the following apply. An abbreviation defined in the present document takes precedence over the definition of the same abbreviation, if any, in 3GPP TR 21.905 [1].

ACN Ambisonic Channel Number

ADC Analog-to-Digital Converter

AEC Acoustical Echo Cancellation

AGC Automatic Gain Control

AR Augmented Reality

BLD Back-Left-Down

BRU Back-Right-Up

CI Confidence Interval

DMA Differential Microphone Array

DOA Direction Of Arrival

FLU Front-Left-Up

FOA First Order Ambisonics

FRD Front-Right-Down

HOA High Order Ambisonics

HOA2 Second Order Ambisonics

HOA3 Third Order Ambisonics

IVAS Immersive Voice and Audio Services

IRT-cross Institute for Radio Technology cross

MASA Metadata-Assisted Spatial Audio

MASP Microphone Array Signal Processing

MEMS Micro-Electro-Mechanical Systems

M/S Mid-Side

ORTF Office de Radiodiffusion-Television Français

OSS Optimal Stereo System

SN3D Spherical Harmonics Normalization 3D

TWS True Wireless Stereo

UE User Equipment

VR Virtual Reality

# 4 Size and structure evolution of UEs

## 4.1 Mobile phones

Since 2012, the structure size of mobile phones has been rising in length, width, and depth, indicating a continuous increase in mobile phone size. This may be in response to the strong demand from consumers for multimedia and gaming functions on their phones, as well as the increasing requirements for microphone and camera quantity and battery consumption. The evolution trend of mobile phones is towards full screen, which provides a market foundation for the increase in screen size. The detailed data of structure size are listed in Annex A.1

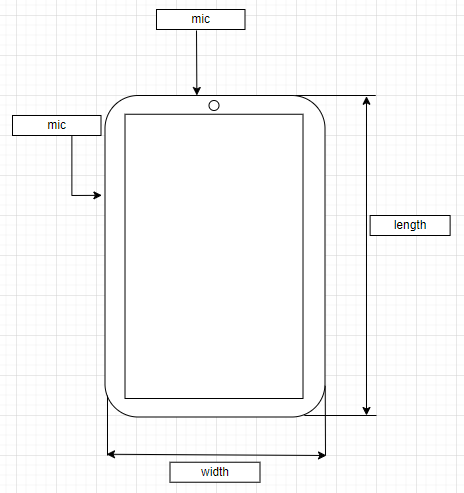
* The maximum values of length, width, and depth are 168.78mm ,80.6mm and 9.92mm.
* The minimum values are 123.8mm (L), 58.6mm (W), and 6.4mm (D).
* The average values are 152.65mm (L), 73.17mm (W) and 8.08mm (D).
* The 95% CI are length, width, and depth (149.60 mm,155.69 mm), (71.92 mm,74.42 mm) and (7.85 mm,8.31 mm).

## 4.2 Headphones

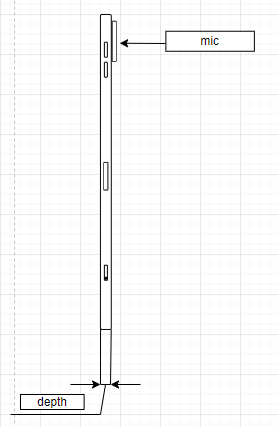
Nowadays, the mainstream earbuds are TWS headphones. Therefore, we investigated some TWS Earbuds. Specifically, the length of all these TWS earbuds measures less than 4cm. Additionally, the depth and width of these earbuds are around 2cm.

## 4.3 Tablets

Tablets, as popular UE, equipped with speakers and microphones. We list 21 devices from 7 brands, it is evident that the size of tablets is significantly larger than that of mobile phones, yet they share a very similar shape. Most of them exceed a height of 20 cm. The minimum length also reaches 19.54 cm. The width is close to 20 cm. The models in the statistics range from 13.48 to 21.49 cm.



**Figure 4.3-1 Tablet front view**



**Figure 4.3-2 Tablet side view**

In addition, the microphone design of tablets now is also very similar to that of mobile phones.

## 4.4 Laptops

Compared to tablets, the primary distinction in laptops is their clamshell structure, featuring a hinged screen and an attached keyboard.

Also, most laptops have larger structure size that of mobile phones. The range in length goes from approximately 28 cm to around 41 cm, resulting in a range of about 13 cm. The widths span from about 18.5 cm to approximately 32 cm. The height range extends from a few tenths of a centimetre (around 0.7) to over 2.6 cm.

图示

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**Figure 4.4-1 Laptop side view**

## 4.5 Watches

Many watches nowadays also have calling capabilities. Nowadays, the smartwatches capable of making calls mainly come in two shapes: circular and rectangle.

For circular type the diameter is around 4.7 cm. And the depth is range from 10.9 to 13 cm

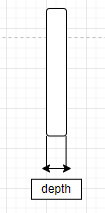
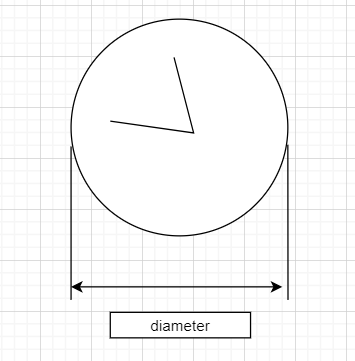


Figure 4.5-1 circular watch

For rectangle type, the lengths vary from 4 cm to 5.7 cm. The widths range from 3.4 cm to 4.57 cm. Heights range from 1.07 cm to 1.49 cm.

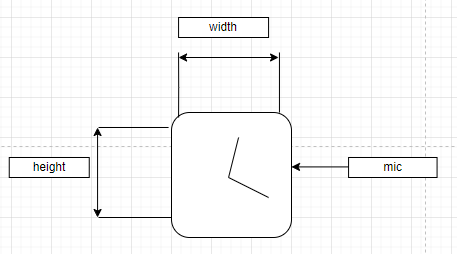


Figure 4.5-2 rectangle watch front view

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Figure 4.5-3 rectangle watch side view

## 4.6 AR glasses

Presently, AR glasses come in a wide range of sizes. Some are substantial and weighty, akin to headband-style headsets, while others are lightweight, resembling ordinary glasses. The larger variants often adopt a headband-style design, whereas the smaller ones are designed to the appearance of regular eyewear, Therefore, the average size of the investigated model is approximately 157.48 cm\*130.92cm\*41.22cm on width, length, and height respectively.

## 4.7 Cars

We have also investigated the dimensions of some mainstream civilian cars. The lengths vary from 445.8cm to 532cm. Widths range from 180.6cm to 208.9cm. Heights fluctuate between 144.2cm and 180.0cm.

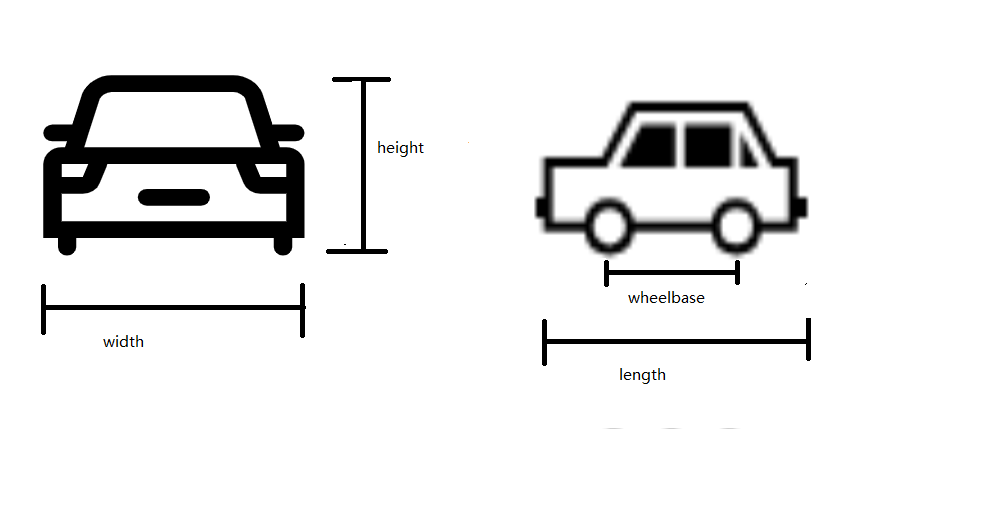


Figure 4.7-1 car front and side view

Due to the demand for voice services, modern cars are increasingly equipped with more microphones, especially electric vehicles. One of the popular microphone placements is to place microphone arrays on one side of the car roof. There are also other configurations, including centralized placement and distributed placement.

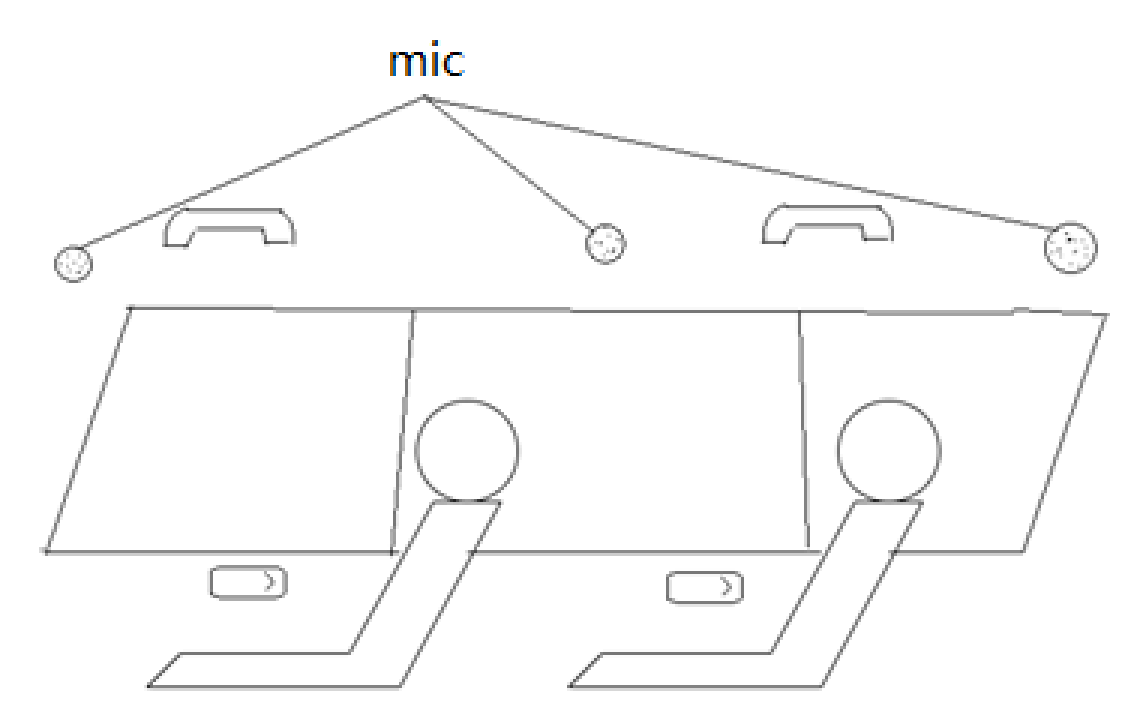


Figure 4.7-2 microphone placement in car

Some models with exterior and interior size are listed in Annex A.7 and A.8.

## 4.8 Conclusion

Due to different structures and sizes in each UE category, possible microphone design (placement, distance between microphones) will be different. Such different microphone designs will be discussed in clause 7.

# 5 Microphones used in audio capture

## 5.1 Introduction

The function of microphone is to convert sound pressure signal to analog electrical signal in circuit.

4 types of microphones popular in the market are described in this section. These microphones have unique advantages in UE's immersive audio. They are classified to dynamic microphone, condenser microphone, MEMS, contact microphone.

## 5.2 Transducer type

### 5.2.1 Dynamic microphone

Dynamic microphone is one of the popular microphones on market. The most advantage of dynamic microphone for UE is it doesn’t require external power; therefore, the entire recording system may become simpler. Another advantage is durability, make it more suitable for loud and high-pressure situation. But it usually has a disadvantage that it is less sensitive to high frequencies.

Dynamic microphone uses a small movable induction coil, which positioned in the magnetic field and is attached to the diaphragm. The current signal generates when the movement of the diaphragm causes the coil to also move within a magnetic field.

### 5.2.2 Condenser microphone

Condenser microphone is another popular microphone on market, especially for immersive audio. Most immersive system is using condenser microphones, like ambisonic microphone and external stereo microphone for mobile phone. It’s popular for its high sensitivity, wide frequency response, low noise. However, the condenser microphone requires a power source, and in the case of most professional condenser microphones, it specifically requires 48V phantom power. Meeting this requirement can be challenging for UE device consider the channel number of immersive audio.

Condenser microphone uses capacitor to convert sound waves to electrical signal. The capacitor consists of two plates, one of them is a diaphragm that vibrates in response to sound waves. The diaphragm vibrates and changes the distance between the two plates. Then the capacitance changes which influences the electrical signal.

### 5.2.3 MEMS microphone

In the past decades, microphone for UE has change from carbon microphones to electret condenser microphones. Recently the MEMS microphone is spread rapidly, benefited from its advantages of high stability and small volumes.

According to the techniques of microfabrication, the MEMS microphone is much smaller and allow integrate other components including preamps, ADC with transducer in one package under the control of integrated microelectronics.

Which means for manufacturers, it much easier to build the capture system, MEMS microphone can output the digital signal directly. In other hand, it allows need to select the component more carefully. Since the microphone is much smaller and very uniform in their mechanical properties, it's suitable for UE and make immersive audio become possible for economic portable UE like mobile phone.

### 5.2.4 Contact microphone

Contact microphone is a type of microphone that senses solid vibrations through direct contact with a surface.

Compared to the acoustic microphones, the contact microphones have the benefit of not to capture sound waves in the air, but to capture mechanical vibrations of the target object. Hence, it’s resistant to noise in air.

Nowadays, bone conduction microphone, which is a special kind of contact microphone, is very popular on TWS headphones. It is used to capture high SNR speech signal even in complex scenarios.

## 5.3 Directional Microphone

### 5.3.1 Introduction

Directivity is a very important part in immersive audio, every immersive audio format has requirement on directivity. Even for object audio, we also need take care of the directivity to avoid the influence of environment noise.

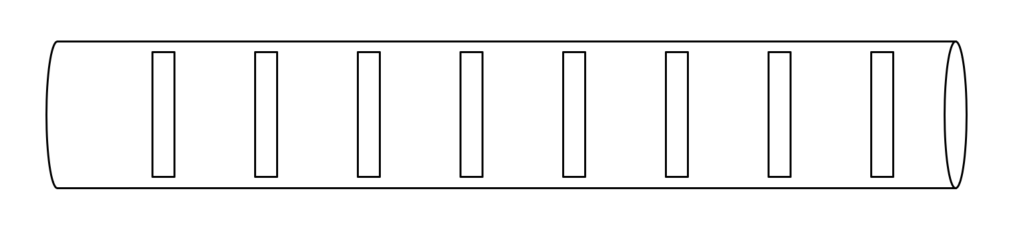
### 5.3.2 Directional microphone capsule

Most directional microphone is using two closely diaphragms that electrically subtracted from each other to provide a range of polar patterns.

### 5.3.3 Interference tube

Interference tube is usually used on shotgun microphones. Make it the more directional than a typical cardioid or supercardioid microphone.

Interference tube is a long, narrow extended tube that is placed in front of the microphone capsule and has multiple small holes along its length. It creates phase shift for sounds arriving from off-axis directions, the off-axis sound will arrive at the diaphragm with varying phase relationships and so partially cancel one another out.

Figure 5.3.3-1 The schematic diagram of interference tube

## 5.4 Binaural acoustic simulation

According to the principle of binaural signal, the typical solution involves placing microphones on each ear of the user or on a model of a human head or ears to capture the binaural cues. This model could be a head with a torso to simulate all influences, including those from the ear, head and reflections from the torso. Alternatively, it could be a single head or simply a model with a pair of ears.

## 5.5 Conclusion

Following advancements in microphone devices, it grants more possibilities for UEs integrated with the miniature microphones to capture audio signals, specifically, the digital MEMS microphone includes preamps, ADC, and clocks, which makes it can directly output digital signals, so audio capture has become significantly more convenient. This innovation is particularly beneficial for small-sized devices according to its size and consistent performance. These miniature microphones can also be used to generate immersive audio in combination with signal processing.

# 6 Audio capture format

## 6.1 Stereo capture

### 6.1.1 Principle of stereo signal representation

The basic idea behind the stereo recording technique is to capture two signals with a proper relationship. By controlling the relationship between the two signals, it creates sound image with spaciousness, direction and depth feeling for listeners. And it can be reproduced through headphones or loudspeakers.

### 6.1.2 Characteristic of stereo capture

Compared to other formats, stereo capture does not aim to accurately reproduce the original sound field. Instead, its focus is on creating convincing illusory sound images for listeners, which is achieved by generating enough perceptual cues. It can provide a natural and realistic experience to the listeners in a limited range of listening zone. And it is more technically mature.

### 6.1.3 Factors that affect stereo capture

The key cues that may influence the quality of stereo capture are interchannel time differences, interchannel level differences and frequency range, which have been discussed since the emergence of stereo audio.

In the past, the discussion of factors that affect stereo capture always revolves around microphone properties (such as directionality and frequency range) and the placement of microphones.

With advancements in audio processing, we now have more methods to control audio signals, which is highly promising for stereo applications. This is especially relevant since UE imposes strict restrictions on hardware due to space constraints. The ability to fine-tune audio signals through processing offers great potential for enhancing stereo performance despite various limitations, but it may also import more influence on audio experience, which needs to be carefully analyzed. Therefore, acoustic design also needs to consider the characteristics of relevant processing.

### 6.1.4 Stereo microphone configurations

#### 6.1.4.1 Introduction

Stereo microphones can generally be classified as spaced, near coincident, baffled, coincident, and it is based on the directional characteristics of the microphones, their angle and distance between them. The following sub-clause presents some of these configurations.

#### 6.1.4.2 Near-Coincident

Near-Coincident using two directional microphones placed close together at an angle is to capture stereo audio. This configuration utilizes the angle and distance between the microphones to create a suitable time and level inter-channel difference. There are number of near coincident configurations which are arranged at specific angles and distances, one of the well know near coincident stereo microphone is

In the ORTF configuration, microphone pair is arranged to mimic the placement of human ears, it uses two cardioid microphones with 17cm apart and at a 110° angle from each other.

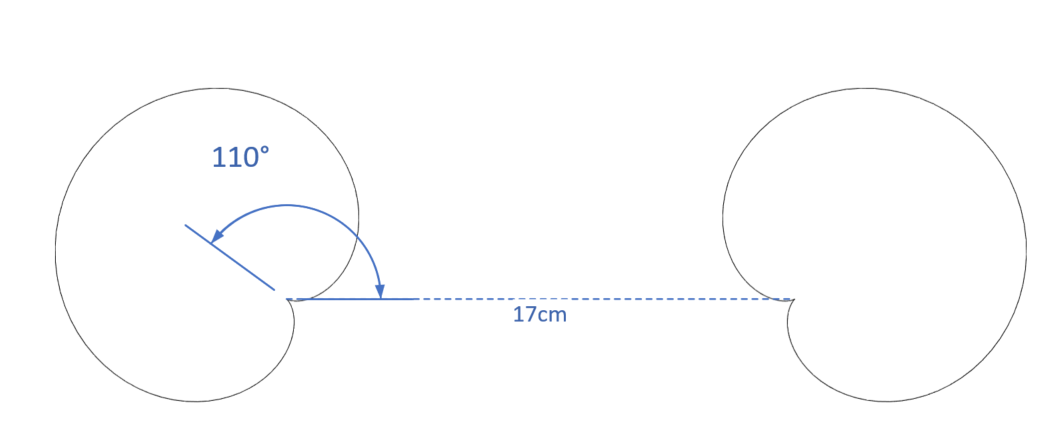
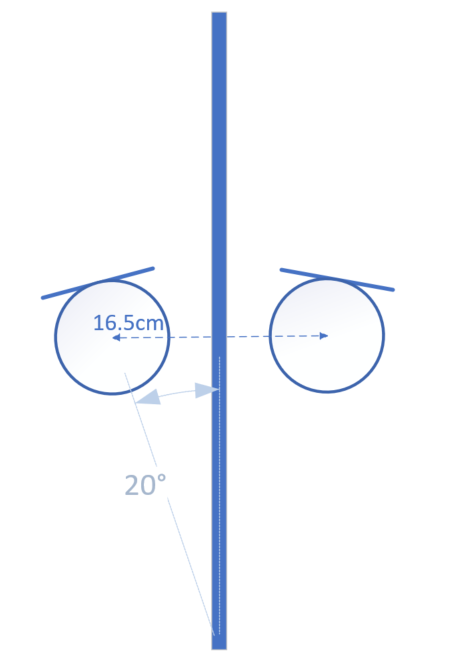


Figure 6.1.4.2-1 The configuration of ORTF stereo microphone

#### 6.1.4.3 Baffled

A baffled configuration is a stereo recording technique that utilizes an acoustic baffle to increase the separation between the left and right audio channels. The baffle is typically a physical barrier that is placed between the two microphones. One of the examples of baffled microphone setup is OSS.OSS method utilizes a specially designed 30-cm disk covered with foam, with two omni-directional microphones mounted on opposite sides of the disk and angled slightly outward at 20°. The capsules of the two microphones are positioned 16.5 cm apart.



**Figure 6.1.4.3-1 The configuration of OSS stereo microphone**

#### 6.1.4.4 Coincident

##### 6.1.4.4.1 Introduction

A coincident stereo microphone consists of two directional microphones placed at an appropriate angle at the smallest-possible spacings. Therefore, sound arrives with equal delay and different level and phase at microphones.

##### 6.1.4.4.2 X/Y

X/Y stereo microphone is commonly using two cardioid microphones ranging from 90-135°.

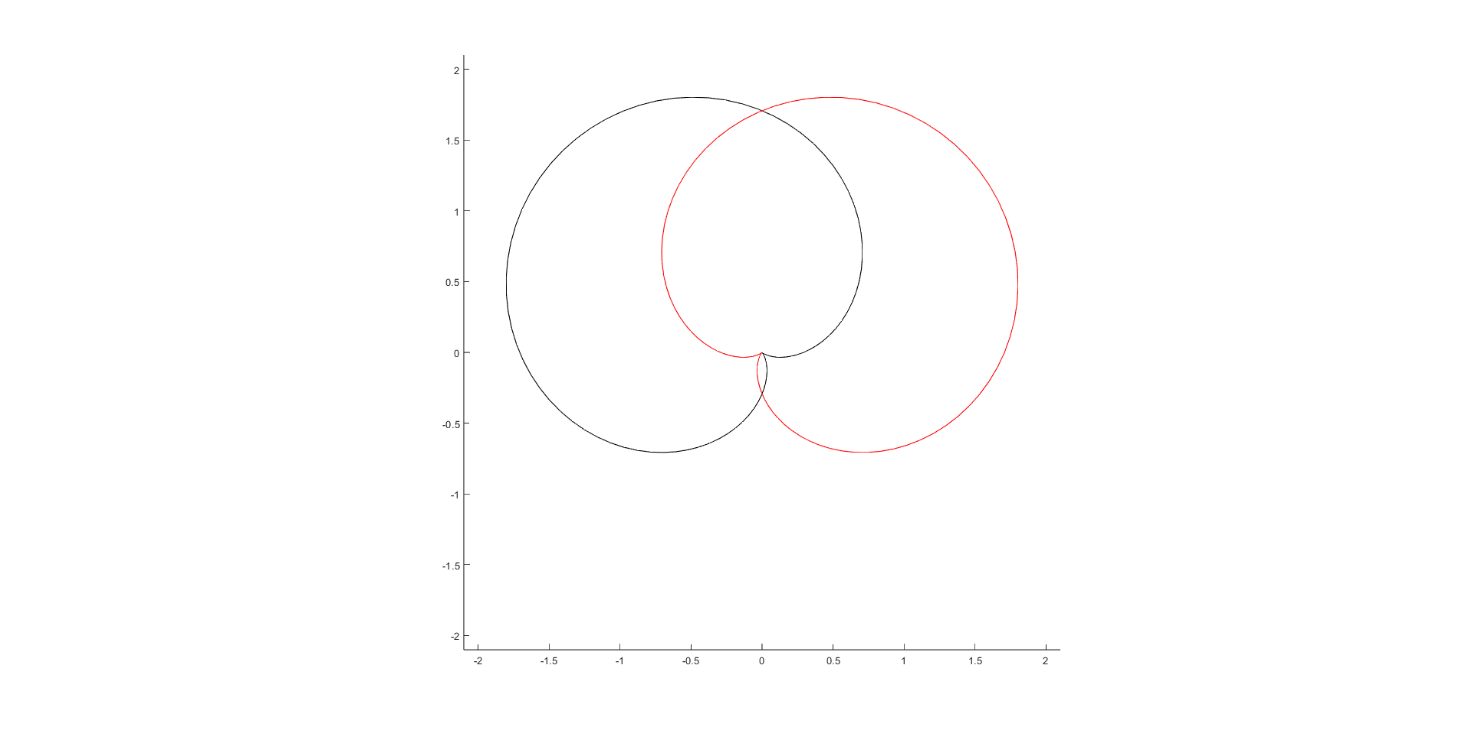


Figure 6.1.4.4.2-1 The configuration of X/Y stereo microphone

##### 6.1.4.4.3 Blumlein

Blumlein stereo microphone consists of two bidirectional (figure-eight) microphones with 90° angle at the same place.

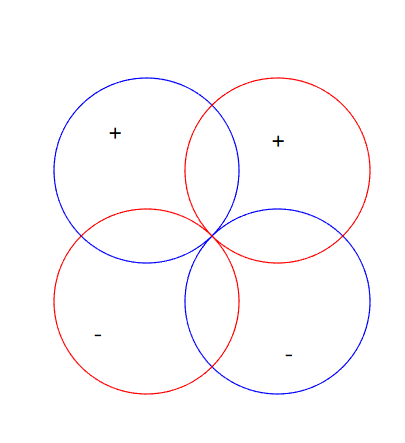


Figure 6.1.4.4.3-1 The configuration of Blumlein stereo microphone

##### 6.1.4.4.4 M/S

M/S stereo microphone using a microphone (usually a cardioid) pointed forward, and a bidirectional (figure-eight) microphone oriented perpendicular to the directional microphone. The figure-eight microphone captures side signal, and the cardioid microphone capture mid signal. Therefore, we can obtain the left and right channel signal through the simple addition and subtraction.

In addition, controlling the ratio of the two signals, different angles can be obtained.

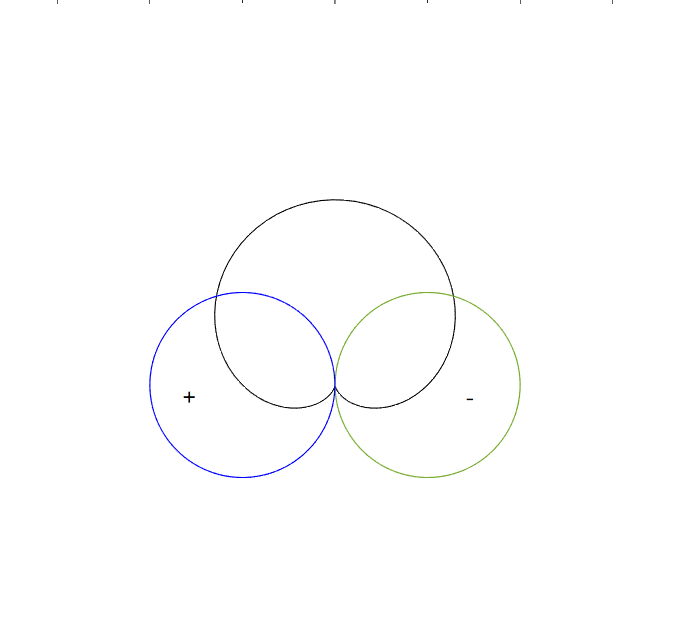


Figure 6.1.4.4.4-1 The configuration of M/S stereo microphone

#### 6.1.4.5 Spaced

The spaced stereo microphone, also known as A/B stereo, is a stereo microphone technique that involves placing two omnidirectional microphones some distance apart from each other. This technique is commonly used with microphone spacings ranging from 0.3-1 meter.

The spaced stereo microphone technique utilizes the distance between two microphones to create a time difference and level difference between the left and right channels. This is caused by the difference in arrival time of sound waves at each microphone, as well as the absorption of sound by the air between the microphones.

NOTE: As most classic spaced configurations involve microphone distances greater than 30cm, which exceeds the size of current mobile phones, this aspect can only be listed for further study.

## 6.2 Spatial audio capture

### 6.2.1 Introduction

Several device form factors require spatial audio capture processing that is carefully designed and tuned for the specific multi-microphone array. In practice, a suitable parametric spatial audio capture analysis and processing is often implied for such devices.

### 6.2.2 Binaural capture

#### 6.2.2.1 Principle of binaural signal representation

The basic idea behind the binaural recording technique is to capture the two signals that form the input to our hearing. By capture these signals in the ears of a listener, it can retain both timbre and spatial aspects, even keep the personal feature in binaural. And it can be reproduced accurately though headphones.

#### 6.2.2.2 Possible issues in binaural capture

Binaural audio can be defined as follows:

“Binaural audio is defined as a two-channel spatial representation of a soundfield as typically captured at the entrance of the ear canals and intended for direct presentation to the left and right ears over headphones”

However, the situation is not always so ideal. In most case, it’s hard to place the microphone just at the entrance of ear canals. So, it may be helpful to figure out what will influence binaural capture, therefore we can get better signal under limited conditions.

#### 6.2.2.3 Factors that affect binaural capture

There are many cues that may influence the quality of binaural capture, e.g., interaural time differences, interaural level differences, interaural phase differences and spectral characteristics. The cues are influenced by the listener’s pinnae, head and body.

Earbuds usually have transducers blocked at the entrance of ear canals for playback, which occupy the most important location for binaural record and the microphone need to be set a few millimetres outside the entrance of the ear. The surface of earbud may also cause the reflection. It can be seen that the reflection from pinnae capture in microphone will be influenced.

#### 6.2.2.4 Differences between binaural and stereo audio

Both binaural and stereo formats consist of two left and right channels. Several differences are outlined in Table 6.2.2.4-1.

**Table 6.2.2.4-1: Differences between binaural and stereo audio**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Format** | **Distance between left and right channels** | **Spatial cues** | **Suggest playback** | **Relationship between interaural differences and interchannel differences** | **Sound image** | **Binaural rendering** |
| **Stereo** | 0 to few meters | Interaural time differences and interaural level differences, | Headphone | Interaural differences equal to interchannel differences. | -90° to 90 ° (see NOTE) | Allowed |
| Loudspeaker | Interaural differences equal to interchannel differences plus differences caused by propagation from speakers to ears | Between left and right loudspeakers | Not allowed |
| **Binaural** | Equal to distance between ears | Interaural time differences, interaural level differences, interaural phase differences and spectral characteristics | Headphone | Interaural differences equal to interchannel differences. | All directions. | Not allowed |
| NOTE: When stereo audio playback on headphones is processed with binaural rendering, the sound image transforms to be positioned between left and right virtual loudspeakers. | | | | | | |

### 6.2.3 Parametric spatial audio capture

#### 6.2.3.1 Principle of parametric spatial audio representation

Spatial, or immersive, audio representations generally enable reproduction of audio scenes where the listener experience can optimally correspond with the real recorded situations and environments. This means, e.g., that a listener can hear audio sources around them in their original directions relative to the listening position and orientation. Faithful reproduction is generally possible via headphones, including head-tracked binaural rendering, or a loudspeaker setup that provides sufficient spatial capability.

Parametric spatial audio describes a spatial sound field according to a parametric representation. In a typical solution, a multi-microphone capture is compressed into a lower number of audio channels and associated spatial parameters. The parameters define the perceptually relevant properties of the sound field (e.g., directional information, how directional or diffuse the sound field is, etc.), while the audio channels define the actual energetic representation of the captured sound field.

The analyzed parameters and audio channels can be further utilized for the synthesis of an accurate spatial audio representation in a desired output configuration. For efficient and realistic synthesis, the directional parameters are mapped into perceptual spatial cues, which are further applied for the transport audio channels. To enhance the quality of the reproduction, the parameters can be analysed based on the desired auditory frequency bands.

Typical processing flow of the parametric spatial audio capture is illustrated in the Figure 6.2.3.1.-1.

A diagram of a cell phone

Description automatically generated

Figure 6.2.3.1-1 Overview of parametric spatial audio capture

A prominent example of a parametric spatial audio representation is the MASA format defined in 3GPP TS 26.258 [5]. Specifically, MASA comprises one (mono) or two (stereo) transport audio signals and metadata.

#### 6.2.3.2 Characteristics of parametric spatial audio capture and representation

Parametric spatial audio capture is typically purpose-fit for the device form factor that utilizes it. There can also be different representations, or a specific capture algorithm can utilize only a subset of parameters that another capture algorithm uses. Therefore, two substantially similar devices can have different capture algorithms or at least different tunings.

Parametric spatial audio capture and representation typically enables relatively low computational complexity for capture processing and encoding, largely because the number of channels in the representation can be lower than the number of originally captured channels.

#### 6.2.3.3 Factors that affect parametric spatial audio capture

Multiple factors may affect the quality and accuracy of the parametric spatial audio capture. A few factors are:

• Dimensions of the capture device (distance and the placement of the microphones)

• Number and the characteristics of the microphones (directivity and frequency response)

• Applied signal processing techniques for the captured multi-microphone signals, e.g., noise suppression and filtering

• Quality of the spatial parameter analysis algorithm and the device specific tuning

Furthermore, due to the above factors, the quality and the accuracy of the parametric spatial capture is not necessarily similar for all the capture directions. This is highly dependent, e.g., on the specific device form factor and its microphone placement/spacing.

#### 6.2.3.4 Multi-microphone configurations in parametric spatial audio

The number and the configuration of the microphones can be arbitrary, but in principle the lowest number of microphones for accurate 2D planar representation is typically 2 for 180° (frontal) capture, and 3 for 360° capture. Furthermore, by increasing the number of the microphones, the whole 3D sound field can be captured accurately. Typically, minimum number for microphones in this case is 4.

The associated direction parameters can be obtained, e.g., by assessing the inter-channel properties of the captured multi-microphone signals. Such properties could be inter-channel time-difference, coherence, and/or level difference. The analysis can be based on suitable frequency bands.

### 6.2.4 Non-parametric spatial audio capture

#### 6.2.4.1 Principle of non-parametric spatial audio representation

Non-parametric spatial audio representation is used to provide spatial audio service at a reference point or area using certain number of audio channel data which have corresponding placements. the key point to the performance of the spatial audio service is to have appropriate audio data based on either standard or non-standard placements. Due to the constraints of the UE device shape, it is very hard to generate the spatial audio representation directly from their embedded acquisition units or even from selected accessory devices. the ordinary solution is to use microphone array to catch raw signals and then do mathematical processing to output the expected results.

Example processing flow of the non-parametric spatial audio capture is referring to Figure 6.2.4.1-1

A black screen with blue lines

Description automatically generated

Figure 6.2.4.1-1 Overview of non-parametric spatial audio capture

#### 6.2.4.2 Characteristics of non-parametric spatial audio capture and representation

The placement of microphones is subject to various restrictions of the end-user devices, the non-parametric spatial audio capture can be used to generate both standard format audio and non-standard format audio. Several standard audio formats which are used as IVAS codec input formats are surround (5.1 and 7.1), surround + height (5.1+4 and 7.1+4), FOA, HOA2, HOA3, Object-based audio. The standard format audio is a necessary part of the interoperable solution between different kind of end-user devices.

Non-parametric spatial audio capture and representation is an important intermediate link joint between originally captured raw signals at sending end and rendered spatial signals at receiving end, it can allocate computational complexity of the end-to-end real-time spatial audio solution into two ends.

The accuracy of the non-parametric spatial audio representation can be significantly different because of the corresponding non-parametric spatial audio capture solution, it is necessary to carefully define the minimum performance requirements for the non-parametric spatial audio representation, based on this, higher performance is always pursued with better solutions.

#### 6.2.4.3 Factors that affect non-parametric spatial audio capture

It is the same as parametric spatial audio capture, refer to section 6.2.3.3

#### 6.2.4.4 Multi-microphone configurations in non-parametric spatial audio

Immersive audio capture technology by microphones has been developed for decades, however, its corresponding microphone configuration is not fit for current mobile phones.

Numerous stereo microphone configurations have been developed to create immersive audio experiences. Several immersive configurations that are compatible with mobile phones are listed here.

##### 6.2.4.4.1 Immersive audio ORTF configuration [6]

6.2.4.4.1.1 ORTF-surround

The "ORTF-surround" configuration evolves from the ORTF stereo technique, consisting of two back-to-back ORTF stereo setups. It utilizes four super-cardioid microphones arranged in a rectangular formation, with each side measuring 10 cm by 20 cm and forming azimuth angles of 80º and 100º. The output from each microphone is individually routed to the corresponding Left (L), Right (R), Left Surround (LS), and Right Surround (RS) speakers to create an immersive audio experience. Refer to Figure 6.2.4.4.1.1-1.

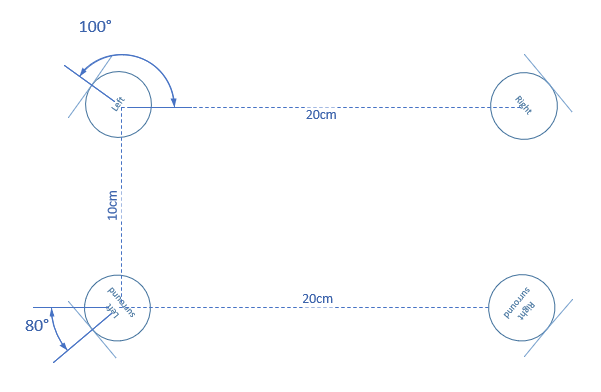


Figure 6.2.4.4.1.1-1 The configuration of ORTF-surround microphone

6.2.4.4.1.2 ORTF-3D

The "ORTF-3D" consisting of two "ORTF-surround" configuration, one is placed directly on top of one another with 90º on elevation Angle, Refer to Figure 6.2.4.4.1.2-1.

A diagram of a circle with circles and lines

Description automatically generated

Figure 6.2.4.4.1.2-1 Left view of ORTF-3D microphone front channels

##### 6.2.4.4.2 Immersive audio M/S configuration

6.2.4.4.2.1 Double-M/S[7]

The "Double-M/S" configuration enhances the traditional M/S configuration by adding an additional rear-facing cardioid microphone. This rear-oriented mic integrates with the existing figure-8 microphone's signal, creating a pair of back-to-back M/S systems that capture a surrounding sound field. And corresponding channel signal can be obtained through the following equation, Refer to Figure 6.2.4.4.2.1-1.:

A diagram of a diagram

Description automatically generated

Figure 6.2.4.4.2.1-1 The configuration of Double-M/S microphone

6.2.4.4.2.2 M/S-3D[8][9]

By incorporating a vertically oriented figure-8 microphone as “Z” signal into the "Double-M/S" configuration, the "M/S-3D" setup can capture the height channel, refer to Figure 6.2.4.4.2.2-1.:

A circle with letters and numbers

Description automatically generated with medium confidence

Figure 6.2.4.4.2.2-1 Left view of M/S-3D microphone

##### 6.2.4.4.3 IRT-cross

Another well-known configuration is the "IRT Cross," which is an equal segment microphone array. This array can be configured with either four cardioid microphones placed 20 cm apart or four supercardioid microphones spaced 14 cm apart. Refer to Figure 6.2.4.4.3-1.

A diagram of a diagram

Description automatically generated

Figure 6.2.4.4.3-1 The configuration of IRT-cross microphone

#### 6.2.4.5 Comparisons between non-parametric spatial audio capture and parametric spatial audio capture

Parametric spatial audio employs a suitable parametric representation for the captured sound field, which is based on the analysis of the raw microphone signals to produce parameter metadata and potentially converting the raw microphone signal into specialized audio channel data.

In contrast, non-parametric spatial audio can only produce the audio channel data without parameter metadata. Once the microphones and their configuration are determined, the raw microphone signals can be converted into expected audio channel data by certain signal processing.

## 6.3 Summary

Principles, configurations, and audio quality factors for achieving immersive capture were discussed. Stereo capture involves recording two audio signals to create a sound image with spaciousness, direction. Spatial capture uses at least 2 microphones to accurately reproduce audio scenes with spatial cues, such as direction and elevation, for immersive listening.

# 7 Microphone integration in UEs

## 7.1 Microphone integration in mobile phones

7

Modern smartphone devices come with inbuilt MEMS microphones supporting more than one microphone, while the top end devices have inbuilt microphones between 3 to 4; mid-range devices support dual microphones. With multi-microphones as a feature, they offer several advantages over devices with mono including improved audio quality, better spatial awareness, more accurate noise cancellation, better sound localization.

The spacing between the multi-array microphones, its polar pattern and the number of microphones varies from device to device. However, generally the spacing ranges from 3cm – 17cm. The following table 7.1-1 covers the specifications of these microphones in smartphones.

Table 7.1-1: MEMS Microphone example characteristics for Multi-array microphones in Smartphone.

|  |  |  |  |
| --- | --- | --- | --- |
| **Number of Microphones** | **Placement of Microphones** | **Spacing** | **Polar Pattern** |
| Dual Microphone  array | Top and Bottom of Bezel | 12 to 17 cm | Omni-directional or Cardioid |
| Bottom of Bezel and rear facing | 10 to 15 cm |
| Triple Microphone array | Top, Bottom of Bezel and Rear Facing | 5 to 17 cm | Omni-direction, Cardioid, directional |
| Quad Microphone array | Top, Dual Bottom of Bezel and Rear Facing | 5 to 17 cm | Omni-direction, Cardioid, directional |

Microphones with 3cm stereo spacing are usually located at the bottom of the bezel (left and right side of USB C-Port), while the larger spacing is achieved with a combination of top, bottom bezel microphone and/or rear facing microphone. Because the user can operate and hold the device in a variety of ways, a combination of these microphones can be activated for stereo voice communication and efficient capturing configuration is possible with advancements in audio processing by means of fine-tune of audio signals through pre-processing which offers great potential for enhancing stereo performance for different user end consumption scenarios such as loudspeaker and/or headphones.

## 7.2 Microphone integration in headphones

Generally, headphone form factors can be divided into 3 categories over-ear, on-ear, in-ear. Nowadays, wireless headphones are quite popular, and these devices are often connected to a smartphone or a portable device via Bluetooth both for speech communication and for audio streaming. These devices are equipped with MEMS microphones supporting more than one microphone. The number and placement of microphones per device category vary from manufacturer to manufacturer with the goal of delivering better sound quality and spatial experiences.

Despite the form-factor for in-ear headphones being comparatively smaller compared to on and over-ear devices, in-ear devices incorporate up to 6 microphones (3 per bud), while on-ear devices incorporate up to 9 microphones, with a major focus on improving user experience.  Tables 7.2-1 and 7.2-2 cover the specification of these microphones for on-ear, over-ear, and in-ear.

Table 7.2-1: MEMS microphone example characteristics for multi-array microphones for on-ear or over-ear devices

|  |  |  |
| --- | --- | --- |
| **Number of Microphones per pair** | **Placement of Microphones** | **Polar Pattern** |
| up to 9\* microphones | up to 3 external microphones per side distributed.  on the outside ear cup. | Omnidirectional |
| 1 internal microphone per side |
| w/wo 1 dedicated microphone for voice (right cup) |

9\* For some headphones (on-ear), up to 9 microphones are available, while others may have fewer than 9 microphones. 

Table 7.2-2: MEMS microphone example characteristics for multi-array microphones for in-ear devices

|  |  |  |  |
| --- | --- | --- | --- |
| **Type** | **Number of Microphones per pair** | **Placement of Microphones per side** | **Polar Pattern** |
| Pod | Up to 6\* | Bottom of the stem (1), Top of the stem (1)  w/wo Inward facing microphone (1) | Omnidirectional /Cardioid |
| Bud | 2 mics located on the outer part of the bud w/wo one inward facing microphone |

6\* Some headphones may incorporate one or two additional bone conduction microphone(s).

The general tendency among wireless headphone manufacturers is primarily focused on delivering better noise cancellation. To achieve this, larger microphone arrays up to 4 per side is used.

## 7.3 Microphone integration in tablets

Tablets share a similar structure with mobile phones but are significantly larger in size. This allows for more flexibility in the placement of microphones, with some tablets accommodating up to five microphones.

Small microphone arrays are also a common feature on tablets. However, due to the less common handheld mode in tablets, microphones near the USB port - the closest location to the mouth in handhold mode - are rarely seen. Instead, microphones are typically located near the front and back camera modules and along the edges of the tablet, refer to table 7.3-1 .

Table 7.3-1 MEMS microphone example characteristics for multi-array microphones for tablets

|  |  |
| --- | --- |
| **Number of Microphones** | **Placement of Microphones** |
| up to 5 microphones | 1-3 on the top of the devices (near the front camera) |
| 1 on near the back camera |
| 1 on the edge of device |

## 7.4 Microphone integration in laptops

Due to the clamshell structure of laptop, in current devices, there are more options for microphone placement. Some are positioned on the screen part, while others are located on the keyboard section.  More potential microphone location resulted in larger microphone distance, and moveable microphone location.

Some popular microphone placements on laptop are explained in following figures:

A screen shot of a computer

Description automatically generated

Figure 7.4-1 Laptop microphone placement 1

A graph with a line and a line

Description automatically generated with medium confidence

Figure 7.4-2 Laptop microphone placement 2

A screen shot of a computer

Description automatically generated

Figure 7.4-3 Laptop microphone placement 3

A drawing of a computer

Description automatically generated

Figure 7.4-4 Laptop microphone placement 4

## 7.5 Microphone integration in watches

Modern watch devices are increasingly equipped with microphones and speakers, enabling them to independently establish speech services.

Some up-to-date models often feature two built-in microphones. Typically, one microphone is located on one edge of the watch, while the second is situated on the opposite edge. The spacing between these microphones generally correlates with the size of the watch, ranging from 3-5cm.

## 7.6 Summary

MEMS microphones are the default choice for the UEs discussed in the above sub-clauses. Each UE category typically includes a minimum of two microphones, enabling multi-channel capture, which may offer improved audio quality, better spatial awareness, enhanced noise suppression, and sound localization compared to a mono microphone. However, to achieve optimal sound quality with a multi-microphone setup, several factors may be considered, such as microphone placement, type, characteristics, user interaction and handling, etc.

Some of the UE designs has narrow spacing between microphones, which may result in poor spatial characteristics and may not provide the best sound quality for multi-channel capture. For UE categories such as smartphones, users can hold and operate their devices in various ways, which can obstruct microphones and affect audio quality, stereo imaging, or spatial awareness. Additionally, variations in hardware quality across different devices and UEs can also lead to inconsistent audio performance, even within the devices of the same UE brand.

To fully benefit from 3GPP IVAS codec for the UEs of various categories, recommendations per UE category such as spacing between microphones, type, characteristics, etc., will be needed without restricting the manufacturer’s flexibility in UE hardware design.

## 7.7 Microphone integration and frequency response

The MEMS microphone package includes a port that allows external sound to enter, while the transducer is shielded by a can, which may be perceived as chambers. These components form a Helmholtz resonator, resulting in resonances. Numerous studies in this field have provided various formulas to calculate such resonators, a rise in specific frequencies can often be observed in numerous MEMS microphones, exhibiting a curve like resonance.

Microphone capture is defined by the electroacoustic properties of the microphone transducer and acoustic properties of the microphone integration. Microphone integration on mobile devices is typically product specific and different products have variation between microphone assemblies due to differences in product mechanics and electronics. Smartphones use MEMS microphone technologies that are typically either top port or bottom port type depending on the product mechanics. The choice of MEMS microphone type influences the microphone port geometry. In smartphone design, microphones in the top and bottom ends can be integrated more similarly to each other, see figure 7.7-1, and when microphones are integrated on other surfaces, e.g., next to the main camera, the design needs to use different mechanical structures.

In addition to differences in microphone integration, the acoustic diffraction from rigid body of the product will influence the overall frequency response of the microphone. Acoustic diffraction is highly dependent on sound source direction due to the non-uniform shape of the smartphone body.

A graph of a number of microphones

Description automatically generated with medium confidence

Figure 7.7-1. Integrated microphone frequency responses (incl. port and transducer) for stereo microphone integration in both ends of a commercial smartphone device.

In general, it is unlike for a mobile device, especially with more than 2 microphones, to have similar microphone frequency response characteristics for all microphones. Two mobile devices with 4 microphones were analyzed indicating differences between typical smartphone microphone integrations (see figure 7.7-2). Microphone frequency responses illustrated in figure 7.7-2 and 7.7-3 provide examples where resonances are clearly audible and need to be compensated with microphone signal equalization to enable high-quality audio capture.

Accurate frequency response data for equalization filter design can be created using multiple techniques, such as acoustic measurements in anechoic chamber, use of lumped parameter component models, or application of numerical acoustic simulation tools. The numerical acoustic methods require detailed acoustic port geometry, which can include information about dust and liquid protection filters or membranes. These filter materials have acoustic impedance that is considered in the acoustic design process. Usually, acoustic characterization of microphone integration is done, or at least verified, using acoustic measurements, because equalization relying on inaccurate frequency response data can lead to further issues.

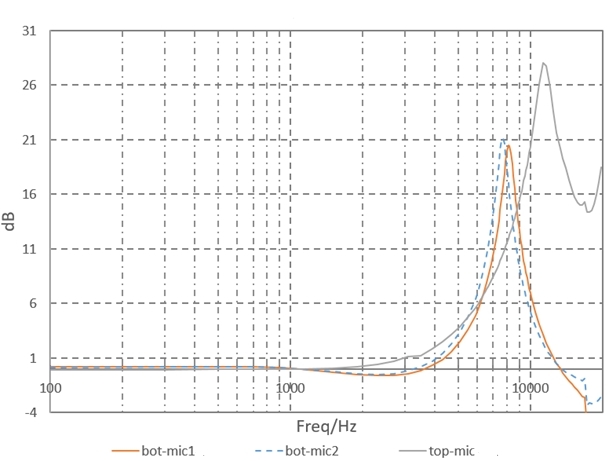
Due to these practical limitations in product design, it would be unrealistic to assume that pressure on the device surface, at microphone port inlet, could be used as an approximation of the pressure on the integrated microphone transducer diaphragm. For example, if this would be the case, the frequency responses, such as presented in figure 7.7-1、figure 7.7-2 and figure 7.7-3 would all be flat.

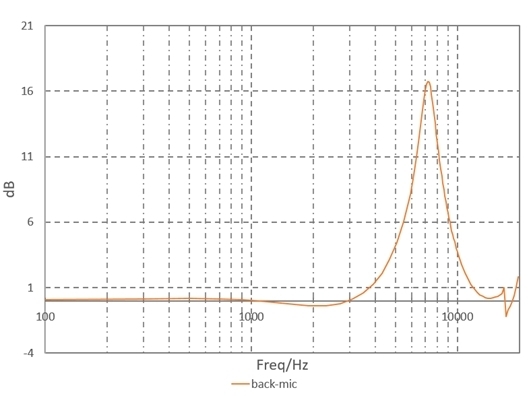


**Figure 7.7-2. Integrated microphone frequency responses (incl. port and transducer) for two commercial smartphone devices with 4 microphones.**

In microphone integration it is generally beneficial to aim for simple mechanical structures that implement a uniform acoustic channel from the surface of the device to the microphone sensor without unnecessary bending, cavities, and other variation in the cross-sectional area of the sound channel. This is commonly achieved when the microphone component is integrated close to the device surface, minimizing the length of the sound port relative to its cross-sectional area. As the hole in the device cover is typically desired to be either small or visually hidden, the acoustic targets of the design are generally best achieved when the length of the microphone port is kept short.

Robust microphone operation during the lifetime of the mobile device requires sealing of the acoustic channel. Sealing and IP protection filters are commonly integrated for easier assembly. The acoustic impedance of the different acoustic filter materials may be included in the numeric analysis of the acoustic channel unless the impedance is low enough to be insignificant.





**Figure 7.7-3. Integrated microphone frequency responses (incl. port and transducer) for one commercial smartphone devices with 4 microphones.**

All microphone integrations include some acoustic filtering effects that typically include resonance. Favorable microphone integration can be characterized by parameters that may be similar for all microphones: microphone resonances are at high frequencies (>10kHz) and resonance magnitude is small with low Q factor. When all microphones of the device are integrated with similar good design practices, this provides a good basis for multi-microphone capture algorithms.

Acoustic scattering from the rigid body of the device is a significant factor in spatial audio capture algorithms for multi-microphone devices. It can be said that free-field approximation using microphone positions will produce inaccurate results especially at high frequencies.

As part of audio design, acoustic measurements can be performed in an anechoic chamber to measure and analyze frequency responses for each integrated microphone as a function of source direction. This is technically a relatively straightforward measurement task, e.g., based on using a turntable to measure multiple source (azimuth) directions in a 360-degree plane. The 3D measurements, including azimuth and elevation directions, require a short series of measurements with different device orientations, or turntable measurements with multiple sound sources. Alternatively, frequency responses can be simulated using numerical acoustic methods.

The frequency response of the raw microphone signal typically appears mostly flat with a pronounced rise in certain high frequency bins, usually exceeding 10dB. To enhance sound quality, selecting the pronounced rise to higher frequency bins can minimize its perceptual distortion.

# 8 Signal processing

## 8.1 AEC

### 8.1.1 Principle of mono audio AEC

The aim of AEC is to minimize or eliminate the acoustic echo that occurs during a full-duplex communication from the other side. A case is described as in Figure 8.1.1-1, a speaker uses a sending device with voice communication capability to play an audio clip (red colour waveform signal), the audio clip is sent through the acoustic environment and received by the device's own microphone which generates the echo signal (blue colour waveform signal) for the sending audio clip. If an adaptive filter can be designed so that its output signal is just the opposite of the echo signal, like the green colour waveform signal, then the following step is to superimpose the blue colour waveform signal with the green colour waveform signal, thus the echo signal is eliminated depending on the performance of the adaptative filter.

A diagram of a speaker

Description automatically generated

Figure 8.1.1-1: diagram of AEC

AEC uses adaptive filters to counteract the impact of echoes and reverberations in the input signal, with the goal of a minimizing error. The general algorithm equations are as follows:







Where, is the input signal, is the desired signal, is the estimated echo signal, is the error signal, is the coefficient of the adaptive filter, is the step size parameter, and M is the length of the adaptive filter.

By minimizing the error and continuously updating the adaptive filter coefficients in an interactive way, the estimated echo signal becomes closer and closer to the desired signal, and finally making the error signal in an acceptable range.

Note: Terminal acoustic characteristics for telephony; Requirements were specified in TS 26.131[13]

### 8.1.2 Challenges for immersive audio AEC

For immersive audio services, the sound is reproduced through multiple speakers while simultaneously using several microphones. When the UE consists of N speakers and M microphones, the number of echo paths generated is the number of speakers multiplied by the number of microphones, i.e., N×M, which is several times the number of echo paths generated by a mono audio communication system. Taking stereo audio as an example, if a stereo audio device uses two speakers and two microphones to create a two-way audio service. In this case, Stereophonic Acoustic Echo Cancellation setup needs to estimate four echo paths. The significant increment in the number of echo paths poses a challenge to the computational complexity of adaptive algorithms. If the mono audio echo cancellation algorithm is directly extended to multi-channel, the algorithm is difficult to converge due to different people, different moments, and different positions of speech, and the adaptive filtering algorithm for mono audio case is not suitable for this situation. Obviously, extending mono audio echo cancellation algorithm directly to multi-channel will result in poor acoustic echo cancellation performance.

### 8.1.3 The current status of the research

The core of multi-channel acoustic echo cancellation algorithm is the same as that of single-channel echo cancellation algorithm - adaptive filtering algorithm. However, multi-channel acoustic echo cancellation faces more difficulties than single-channel AEC, the key point is the non-uniqueness of the solution. The strong correlation of multi-channel input signals will result in non-unique solutions when solving for the optimal filter coefficients, and the echo canceller cannot provide a unique echo path solution. The adaptive filter needs to fit a long impulse response to handle the same length of echo, and this larger filter order requires more historical data, leading to increased algorithm complexity and reduced convergence performance. Therefore, researchers currently address the problem of multi-channel acoustic echo cancellation mainly from two aspects: firstly, removing the correlation of input signals without affecting spatial sound perception, solving non-uniqueness; secondly, improving the adaptive algorithm, allowing the adaptive algorithm to have faster convergence speed and lower computational complexity to form multi-channel situations.

Example of stereo-AEC is referred to Annex B

### 8.1.4 AEC for different UEs

Theoretically, increasing the distance between the microphone and loudspeakers can enhance AEC performance by reducing the echo level coupling from the loudspeakers to the microphones. However, the demand for additional microphones and loudspeakers due to immersive audio brings the distance significantly closer.

This reduction is especially evident in smaller UE, such as mobile phones and earbuds, where the compact size restricts the distance, leading to a higher echo level and shorter echo delay. In some devices, the microphone and loudspeaker may even be placed in the same sound port.

Conversely, larger UE like cars may experience a longer echo delay, but they offer a more stable acoustic environment since all the microphones and speakers for communication are installed within the cabin.

## 8.2 Microphone Array Signal Processing on device

### 8.2.1 Introduction

According to previous investigations, MASP is an essential step for stereo capture, parametric spatial audio capture and non-parametric spatial audio capture, the basic processing is to transform the raw microphone signals into an expected audio representation, and enhancement could be done if necessary.

### 8.2.2 MASP for Channel-based

#### 8.2.2.1 MASP for Stereo

In Clause 4.1, current mobile phones with dimensions of approximately 15cm in length and 7cm in width. Furthermore, a minimum of two microphones is required for stereo audio capture. Consequently, it is logical to use the most basic microphone array configuration as an example: two microphones positioned at a distance of less than 15cm or 7cm, depending on the orientation of mobile phones. So this subchapter will focus on how to complete microphone array signal processing for producing stereo signals based on such microphone array.

### 8.2.3 MASP for Binaural

According to clause 6.2.2, binaural capture on UE appears to be the sole format capable of directly obtaining audio from the raw microphone signals via the earbuds' microphones, enhancement processing could be done for better performance.

### 8.2.4 MASP for Scene-based

#### 8.2.4.1 FOA

FOA signal model is very clear, it consists of four coincident signals: W, X, Y and Z, where W is an omnidirectional signal, while X, Y and Z are figure 8 directional signals aligned with the cartesian coordinate axes. So, the aim of the microphone array signal processing for FOA is to generate standard four coincident signals [2].

#### 8.2.4.2 Matrix on current FOA microphones

The current FOA microphones utilize a tetrahedral configuration, which comprises four cardioid microphones oriented in the directions of FLU,FRD,BLD,BRU. The W, X, Y, Z component are produced through matrix multiplying of the four cardioid signals, refer to equation(1). not follow the SN3D and ACN channel order.

#### 8.2.4.3 HOA

In ambisonic microphones, a minimum of microphones is required to capture N order HOA. Consequently, a second-order HOA necessitates at least 9 channels of ambisonic microphones. The number of microphones on most smartphones is limited to 4,therefore, obtaining HOA microphone array on current microphones configuration of smartphones may be difficulty, however, there are still some relevant researches on upmixing FOA signals to HOA signals such as: the first solution is to interpolate the FOA to HOA signal , as suggested by various studies refer to[14][15][16];The second solution is to utilize of a generative model capable of translating FOA into HOA signal, as refer to [17]; Thirdly, some signal-dependent technologies, such as parametric spatial audio, have the capability to analyse the captured signals and subsequently convert them into an excepted HOA format[18].

### 8.2.5 MASP for MASA

MASA format signals consist of audio signals and metadata. The metadata refer to 26.250[12] are derived from analysis of microphone raw signals, so microphone array signal processing is an essential module for producing MASA signal.

### 8.2.6 MASP for Object-based

According to 26.250 [12], Object-based audio consists of 1-4 individual mono object streams with associated metadata. Many existing technologies can be used to obtain object-based audio.

#### 8.2.6.1 Mono object stream

The mono object stream may need audio with high quality and sufficient SNR, characteristics that closely match the existing mono audio solution. Consequently, the mono object stream may be derived from the current mono audio solution provided by UE.

#### 8.2.6.2 Associated Object Metadata

A minimal set of object metadata associated is the object position in the polar coordinate system described using azimuth [-180°,180°] and elevation [-90°, 90°] angle.

DOA is commonly utilized in current audio services, it is to determine the direction of the audio that needs to be processed. The direction information can also be set as associated object metadata to describe the position of one audio object.

## 8.3 Beamforming

### 8.3.1 Introduction

Research on microphone array beamforming began in the late 1960s, although some basic principles can be traced back to the 1930s when directional microphones were invented. Early work in this field was strongly influenced by sensor array theory developed in the radar and sonar fields.

Beamforming is a very popular technology to achieve target directivity, though it’s mostly used for mono speech now, it is great potential in immersive audio. There are also many studies in this area.

This proposal starts with two fundamental technologies: Delay-sum and differential. And aim for the suitable solution for immersive audio on UE.

### 8.3.2 Delay-sum microphone

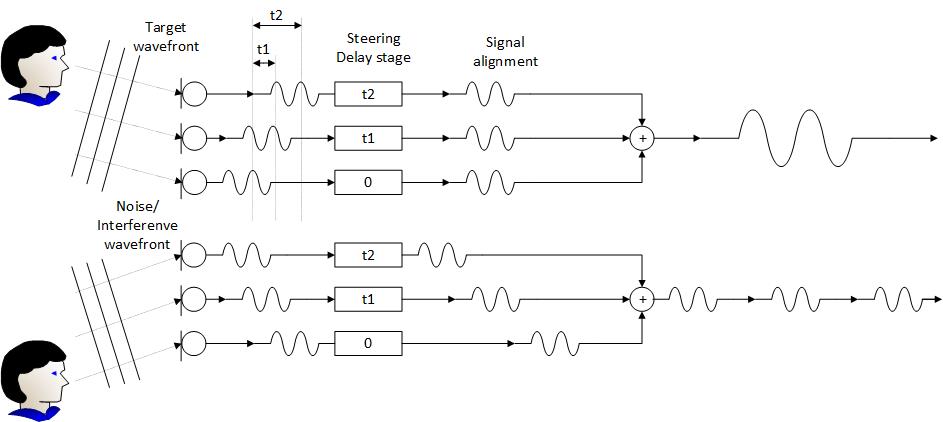


Figure 8.3.2-1 The diagram of Delay-sum microphone array

The basic idea of this technology is to delay the output of each microphone by an appropriate amount of time. The phase relationship between the microphones is carefully controlled to ensure that the signal form desired direction have the same phase so that they can be reinforced.

Though the delay-sum microphone array can obtain a very sharp directionality. However, the biggest problem with this beamformer is that its beam pattern changes significantly with frequency.

### 8.3.3 Differential microphone array

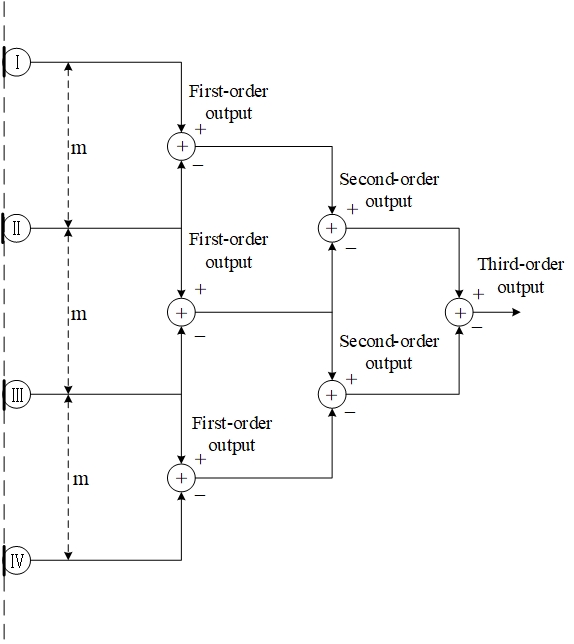


Figure 8.3.3-1 The diagram of Differential microphone array

In DMA, the signals from two or more microphones are subtracted from each other to create a special directivity. The traditional directional microphone can also be seen as a special kind of differential beamforming.

By adjusting the weight and phase of the differential signal, we can all get different directivity like: cardioid, bidirectional (Figure-8), supercardioid, hypercardioid, subcardioid (wide cardioid).

Due to the smaller spacing between microphones, the size of array is usually smaller, making it easy to integrate into UE such as earphones, mobile phones, etc. Another characteristic of DMA is that its directivity is frequency-invariant; therefore, they are suitable for processing broadband speech and audio signals.

## 8.4 Noise reduction

The needs of noise reduction depend on certain usage scenario or sometimes specific solutions, for example, for office scenario mainly consists of speech components, noise reduction is highly needed, however, for concert application scenario which includes various of music instruments and other atmosphere audio components, noise reduction may not be needed, in this case, moreover, audio scene recognition may be also needed for identifying specific scenarios

## 8.5 Conclusion

The raw microphone signals are used for generating the expected format audio signals using MASP to get satisfied audio signal quality, some necessary signal processing modules such as AEC and possible NS are needed for enhancing the quality of the raw microphone signals.

# 9 Example audio capture processing solutions

## 9.1 Capture Scenarios

### 9.1.1 Telephony communications

**Capturing Type**: Multi-Microphone Capturing

**Description**

**Summary**

Call was established between Tom and Harry.

Tom device has multi-microphone capturing capability and Harry conversing via headphones connected to his communication device.

During the conversation with Harry, Tom wishes to share his experience and he changes the orientation of the portable communication device from portrait to landscape.

Tom device activates suitable microphone array configuration based on orientation of the device to maintain its intended position and to allow the listener (Harry) feel immersed in the experience sharing, providing a natural and enjoyable listening experience.

**User Story:**

Tom planned vacation with his friends, and they are in the Bhutan airport. One of Tom’s friend, Harry who is part of travel had to drop out of the vacation at the last minute. Harry felt devastated as he called Tom to break the news. To lighten up Harry’s mood and ensure he didn’t feel left out, Tom came up with an idea of sharing vacation experience with Harry daily. Tom knew it wasn’t the same as having Harry there in person, but he determined to make Harry feel like a part of the trip, even from afar. As Tom and rest of the friends are at the observatory deck of the airport, he decided to share his experience from day-0 (flights land off - takeoff, airport ambience, picturesque mountains in the backdrop etc.,) to Harry. Tom extends his hand holding his communication device in landscape mode towards the flight landing and take off with beautiful mountain view at the background. Harry can now view and listen to the airport observatory deck scene clearly which brought a smile on Harry’s face, as he feels he is part of the scene. As Tom and rest of their friends embarked on their vacation, he stayed true to his promise by giving virtual tour of day’s highlights to Harry.

**Device**

UE (Smartphone, Tablet), Headphones (Over the ear, on ear, In ear)

**Pre-condition:**

Tom’s UE implements multi-microphone capture with activation of relevant microphones.

Headphone connected to Harry’s UE

**Feasibility**

Availability of Multi-microphone capture is getting more common on smartphones.

**Potential Processing Solutions**

Analog-Digital Conversion (ADC), Echo Cancellation, Noise Suppression, Automatic Gain Control, activation of suitable microphones based on device orientation.

## 9.2 End-user device (UE) characteristics/prerequisites

### 9.2.1 General

Support of immersive communication requires suitable integration of electroacoustic transducers, namely microphones and loudspeakers. Current smartphones are characterized by a large display and a slim body, which is a challenging shape for spatial audio capture devices. A device’s shape influences the spatial capture characteristics, and spatial capture typically requires parametric audio capture techniques or suitable modeling to support more uniform performance for different sound source directions.

Current smartphones typically have at least 2 microphones, which is sufficient to support immersive voice and audio capture for a wide range of use cases and applications.

While immersive voice and audio playback can be based, e.g., on rendering for headphones or external loudspeaker systems, stereo and immersive playback can be supported also on the mobile device itself. The number of loudspeakers and their locations in the device together with the rendering processing have an impact on the perceived immersion of the loudspeaker playback. Loudspeaker placement relative to the microphone locations influences both the (spatial) audio capture performance and requirements of the AEC solution.

### 9.2.2 Number and placement of microphones

Spatial audio capture requires at least two microphones, but for rich capture of audio scenes using more microphones is recommended. Two microphones can be used to support stereo recording, and it can be recommendable to implement, e.g., symmetrical microphone integration and placement at the ends of the device to achieve a symmetric stereo image.

Spatial audio capture supporting 360-degree spatial capture in a 2D plane can be supported with 3 microphones. It is common that stereo recording microphones are complemented with a third microphone integrated on the back cover of the device supporting spatial audio capture aligned with the optical axis of the main camera.

The practical aspects related to microphone placement include the detailed mobile device form factor (geometry), which is related to how the device is used, and how user’s hands might interfere audio capture, e.g., either by blocking or disturbing any of the microphone inputs.  Acoustic performance of 360-degree capture is dependent on microphone placement to ensure robust direction analysis for different sound source directions.

For immersive voice and audio use cases with higher spatial fidelity and flexibility, 4 or more microphones can be considered for supporting a full 3D spatial audio capture in both landscape and portrait device orientations. Multiple microphones can improve spatial resolution of audio capture and increase robustness in different usage environments, e.g., by allowing more effective reduction of disturbing wind noise.

Sufficient distance between microphones and loudspeakers can improve AEC performance by reducing the echo level coupling from loudspeakers to the microphones. More details on loudspeaker placement are provided in the following.

9.2.3 Loudspeaker number and placement of loudspeakers

In order to produce immersive (stereo or spatial) playback over loudspeakers integrated into a mobile device, at least two loudspeakers are needed. When playback is active, the number and placement of the loudspeakers have an effect also on the spatial audio capture, e.g., due to interaction with AEC.

Two loudspeakers in a mobile device enable direct stereo content playback and, with suitable rendering processing, can provide an adequate level of immersive experience for the front of the listener. It is straightforward to achieve a wider stereo image extending the physical loudspeaker locations, but creating real feeling of immersion around listener’s head so that sounds are perceived as coming also from behind is very challenging.

Using similar speaker components and placing the speaker outlets symmetrically in the device generally provide the best basis for a high-quality playback. It is beneficial to have the loudspeaker outlets at the device ends so that when listened to in landscape mode, the stereo image will be at its widest. If the loudspeaker ports are facing towards the user, the spatial audio quality can be further improved, and the audio performance is more consistent and independent of device handling, namely interaction effects with user’s hands and grip. More than two loudspeakers can be used especially in larger mobile devices, e.g., in tablets and foldable smartphones to provide favorable stereo loudspeaker pairs at different usage orientations and device configurations.

## 9.3 Capture solution for end-user devices

### 9.3.1 Overview

Support of immersive voice and audio services by end-user devices requires successful combination of several audio technologies and appropriate product design for taking full advantage of the new immersive capabilities. Relevant devices (UE) can come in many shapes and sizes (form factors) for different use cases, and even traditionally dominant UE form factors such as mobile devices can be expected to be used in new ways, e.g., multiple orientations (landscape and portrait) in different use cases and applications that provide immersive voice and audio communication.

Multi-microphone capture is used to get expected audio signals for end-user devices, the following figure 9.3.1-1 illustrates one example process of generating audio signals.

A diagram of a process

Description automatically generated

Figure 9.3.1-1 example process of generating audio signals.

### 9.3.2 Compensation

Compensation block is used to improve the quality of microphone signals, specifically to smooth the frequency responses and minimize the mismatch within microphone arrays. One of the classic solutions is using the EQ filter to change the responses of the microphone signals. Generally, it usually smooths the microphone response of each channel according to the measured microphone response, which makes the microphone signals comparable to each other.

### 9.3.3 Enhancement

#### 9.3.3.1 Introduction

Enhancement block consists of different multiple operations which aim at improving audio quality considering the targeted audio source or sources. These operations can include for example AEC, noise reduction, audio focusing, etc.

#### 9.3.3.2 General considerations

Modern UEs, such as smartphones, typically come with a minimum of two microphones, which may be spatially placed to support stereo and/or spatial audio capture. Users may hold and operate their UEs in landscape (horizontal) or portrait (vertical) mode. Additionally, sometimes user’s hands might interfere audio capture. Based on user interaction with the UE, the audio capture settings can be adjusted accordingly to optimize the multichannel capture performance based on the intended use.

#### 9.3.3.3 AEC

AEC is typically performed separately for each microphone signal, but alternative solutions can also be considered. The target of AEC processing is to remove the loudspeaker signal component from the microphone signals based on a reference signal. In the case of stereo playback both stereo channels are needed as reference inputs for the AEC.

The baseline approach is to apply traditional Acoustic Echo Cancellation on the individual microphone channels. Traditional AEC solution has been to use linear AEC filter which is followed by residual echo suppression (RES). Nowadays RES is often implemented using DNN. Recently, solutions in which the whole AEC is managed with a single DNN have been introduced.

#### 9.3.3.4 Noise reduction

##### 9.3.3.4.1 Introduction

In monaural speech audio, the main emphasis is on capturing the speech signal, however, spatial audio offers the additional advantage of presenting the ambience. As a result, certain ambient sounds, which might be dismissed as background noise in monaural speech audio, are effectively conveyed in spatial audio. The interpretation of noise varies between monaural and spatial audio. Although device floor noise like microphone noise and wind noise are still classified as noise, other non-speech sounds originating from the actual environment enhance the atmosphere and may be considered effective signals in spatial audio according to scenarios.

##### 9.3.3.4.2 Wind noise reduction

The baseline approach is to apply wind noise reduction on the individual microphone channel by non-linear signal processing. A DNN based noise reduction/speech isolation trained on wind noise is also found to be effective to reduce wind noise. Such a system performs well to maintain speech but incurs a higher processing costs and latency.

##### 9.3.3.4.3 Microphone noise reduction

Microphone noise reduction targets to remove self-noise generated by the microphones. It is generally based on defining the noise floor of the microphones.

##### 9.3.3.4.4 Background noise reduction

Background noise reduction can be used to increase intelligibility of the captured speech. It generally makes audio more pleasant to listen to and can be used to remove irrelevant components from the captured audio. Depending on the use case, background noise reduction may only remove continuous noise such as air-conditioner noise or traffic noise, or it may, e.g., aim at removing everything but speech from the captured audio. Content or context-based classification and processing can be employed if different noise reduction processing is desired, e.g., for speech and music. For immersive voice and audio, background noise reduction settings may be more contextual than for traditional mono voice and audio. Noise reduction can also be required for accessibility purposes. DNN-based solutions are commonly used for noise reduction.

##### 9.3.3.4.5 Audio focusing

Audio focusing can be used to focus spatial audio capture into preferred direction. The focus direction can be defined automatically or manually depending on the use case. With suitably selected microphone locations good focus performance can be achieved using beamforming. Audio focusing can be used for content creation or accessibility purposes.

### 9.3.4 Audio format generation

#### 9.3.4.1 Introduction

Th audio format conversion is used to convert the enhanced microphone signals into an expected format audio signal. The following clauses give example processing for smartphone devices.

#### 9.3.4.2 Example of stereo processing

The stereo processing transforms the microphone signals into a standard stereo audio. It employs two or more microphones on the smartphone to create left and right channels. As the stereo audio, sounds coming from different angles present varied ICTD and ICLD. Concurrently, sounds from various angles present a phase difference between the microphones, which can be leveraged to modify ICTD and ICLD for different degrees. A transforming matrix could be constructed based on this information, and technologies such as beamforming may be utilized.

#### 9.3.4.3 Example of scene-based audio processing

##### 9.3.4.3.1 Introduction

The example solution uses a content-based processing module and an ambisonics upmixer module to get scene-based audio signals.

##### 9.3.4.3.2 Content based processing

Content based processing is an optional set of processing that can greatly enhance spatial experience by identifying the content type and applying specific enhancements. Since the processing is content dependent, a general audio classifier or a speech isolation processing is necessary to identify regions of interest. Classification across music, speech and background noise has been found suitable for relevant scenarios. A real-time classifier might have delayed response to events, and false transitions might be triggered due to low or no lookahead. A classifier confidence smoothing, or a state machine can be employed to minimize false transitions and identify class switching events.

##### 9.3.4.3.3 Ambisonic upmixer

This block is responsible for mapping the multi-microphone capture to first order ambisonics or higher. Out of the various techniques to upmix a multi-microphone capture to FOA, a perceptually designed static upmix matrix yields reasonably accurate spatial performance with few or no drawbacks. The response per frequency band is generated across each microphone towards each ambisonic channel using: i) a model of how each microphone responds to the incoming sound field from a dense set of directions, based on finite element method simulations which account for the 3D placement of microphones across device body structure and resultant acoustic energy transfer; ii) a perceptually-motivated optimisation where the complex upmix matrix coefficients are determined based on the data computed at the simulation step, and a target perceptual spatial accuracy. These steps of analysis, simulation and upmix design are performed offline once per device by assuming a simpler 3D geometry of the device and microphones as point sinks.

The upmixer utilizes the static matrix and applies per frequency band transformation to achieve ambisonic channel output.

#### 9.3.4.4 Example of parametric spatial audio processing

##### 9.3.4.4.1 Introduction

The example solution uses a downmixing module and a spatial analysis module to get parametric spatial audio signals (e.g., MASA).

##### 9.3.4.4.2 Downmixing

With parametric spatial audio capture, output spatial audio can be synthesized from a number of audio channels (e.g., one or two) and metadata. Therefore, the number of audio channels can generally be reduced following the audio capture. This can be achieved, e.g., by selecting one or two representative audio channels from the audio enhancement block output.

##### 9.3.4.4.3 Spatial analysis

The target of spatial analysis in parametric spatial audio capture is to estimate spatial properties of the captured audio signal (audio scene) and generate metadata, which can be later utilized in spatial synthesis or rendering. Spatial analysis uses information of the device shape and the locations of the microphones. It is common to perform spatial analysis for frequency domain sub-bands, and analysis can be based, e.g., on coherence and level analysis between the microphone signals. To make sure spatial analysis works properly, it is important that echo is properly removed from the captured signal (see, AEC in clause 9.3.4.2) and, on the other hand, that audio enhancement processing (see clause 9.3.4) has maintained relevant spatial cues in the signals.

In an example spatial analysis, the direction of one or more dominant sound sources are analyzed for every sub-band. In addition, the directional energy and other spatial parameters are estimated. For example, the directional energy can be a ratio relative to the total energy of the corresponding sub-band. Together the analyzed parameters form the metadata for the parametric spatial audio format. The selected audio signals (e.g., mono or stereo) and the analyzed metadata can then be provided as input to spatial synthesis or used, e.g., in audio transmission (as codec input).

### 9.3.5 Post-processing

Post-processing which typically the AGC is utilized to adjust the signals to a suitable level. AGC typically also includes limiter which is designed to prevent signal saturation.

# 10 Conclusions and Recommendations

Editor’s Note

* Provide recommendation on potential work for audio capturing based on the findings in this study.

Editor’s Note: the chapter structures are for further update.

# Annex A: UE size

## A.1 Mobile phone size

### A.1.1 Structure Size

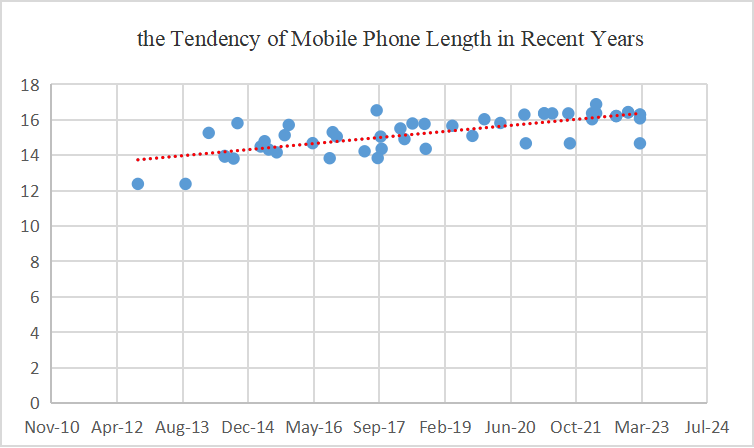
#### A.1.1.1 Introduction

Since 2012, the structure size of mobile phones has been rising in length, width, and thickness, indicating a continuous increase in mobile phone size. This may be in response to the strong demand from consumers for multimedia and gaming functions on their phones, as well as the increasing requirements for microphone and camera quantity and battery consumption. The evolution trend of mobile phones is towards full-screen, which provides a market foundation for the increase in screen size.

#### A.1.1.2 Length

The length of mobile phones has gradually increased from 12.38cm in 2012 to 16.88cm in 2022, with an average length of 15.26cm, according to the investigation, showing an upward trend. With the development of mobile phone models, some phones are no longer limited to the 16:9 aspect ratio, e.g., there are now styles with 18.5:9 and 19.5:9. Although high aspect ratio screens can display more information, most video contents are still in the traditional 16:9 format, so too high an aspect ratio is not conducive to the video display.

The tendency of mobile phone length in recent years is shown in Figure 4.1.1.2-1

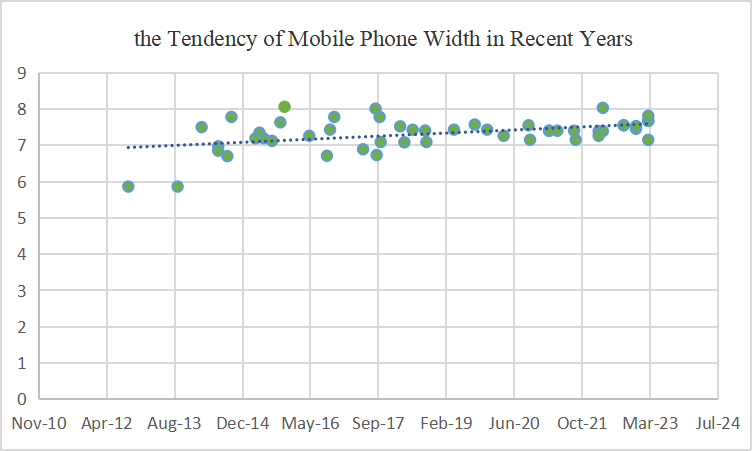


**Figure A.1.1.2-1 The tendency of mobile phone length**

#### A.1.1.3 Width

According to the mobile phone data surveyed, the width of mobile phones was around 5.86cm in 2012, while in 2022, the width of mobile phones was changed to around 7.55cm, with a maximum value of 8.06cm. In recent years, the average width of mobile phones has been 7.32cm, and an increment in the length of mobile phones generally follows an increment in width. This is a reasonable evolution tendency for the purpose of function requirements and appearance

The tendency of mobile phone width in recent years is shown in Figure A.1.1.3-1

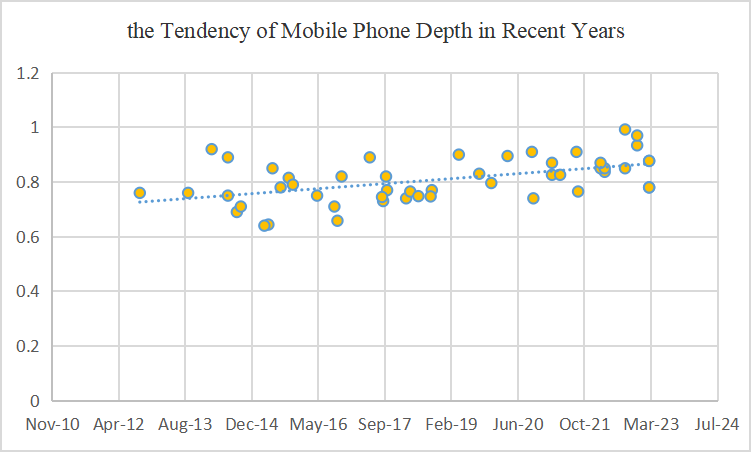


**Figure A.1.1.3-1 The tendency of mobile phone width**

#### A.1.1.4 Depth

Among the phones investigated, the thinnest one measures 0.64cm, the thickest one measures 0.992cm, and the average thickness is 0.81cm.

The tendency of mobile phone width in recent years is shown in Figure A.1.1.4-1



**Figure A.1.1.4-1 The tendency of mobile phone depth**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Model | Date  (MMM-YY) | Length(mm) | Width(mm) | Depth(mm) |
| 1 | Mar-23 | 146.7 | 71.5 | 7.8 |
| 2 | Mar-23 | 160.8 | 78.1 | 7.8 |
| 3 | Mar-23 | 162.9 | 76.7 | 8.77 |
| 4 | Mar-23 | 162.9 | 76.7 | 8.77 |
| 5 | Dec-22 | 164.07 | 74.53 | 9.34 |
| 6 | Dec-22 | 164.35 | 75.29 | 9.7 |
| 7 | Sep-22 | 162.1 | 75.5 | 8.5 |
| 8 | Sep-22 | 162.1 | 75.5 | 9.92 |
| 9 | Apr-22 | 168.78 | 80.31 | 8.37 |
| 10 | Apr-22 | 163.7 | 73.9 | 8.5 |
| 11 | Mar-22 | 163.7 | 73.9 | 8.5 |
| 12 | Mar-22 | 160.3 | 72.6 | 8.7 |
| 13 | Sep-21 | 146.7 | 71.5 | 7.65 |
| 14 | Sep-21 | 163.6 | 74 | 9.1 |
| 15 | May-21 | 163.6 | 74 | 8.26 |
| 16 | Mar-21 | 163.6 | 74 | 8.7 |
| 17 | Mar-21 | 163.6 | 74 | 8.26 |
| 18 | Oct-20 | 146.7 | 71.5 | 7.4 |
| 19 | Oct-20 | 162.9 | 75.5 | 9.1 |
| 20 | Apr-20 | 158.2 | 72.6 | 8.95 |
| 21 | Dec-19 | 160.3 | 74.3 | 7.96 |
| 22 | Sep-19 | 150.9 | 75.7 | 8.3 |
| 23 | Apr-19 | 156.6 | 74.3 | 9 |
| 24 | Sep-18 | 143.6 | 70.9 | 7.7 |
| 25 | Sep-18 | 157.68 | 74.06 | 7.47 |
| 26 | Jun-18 | 157.91 | 74.27 | 7.48 |
| 27 | Apr-18 | 149.1 | 70.8 | 7.65 |
| 28 | Mar-18 | 155.1 | 75.2 | 7.4 |
| 29 | Oct-17 | 143.6 | 70.9 | 7.7 |
| 30 | Oct-17 | 150.5 | 77.8 | 8.2 |
| 31 | Sep-17 | 138.4 | 67.3 | 7.3 |
| 32 | Sep-17 | 165.32 | 80.09 | 7.45 |
| 33 | Jun-17 | 142.2 | 68.9 | 8.9 |
| 34 | Nov-16 | 150.5 | 77.8 | 8.2 |
| 35 | Oct-16 | 153 | 74.3 | 6.58 |
| 36 | Sep-16 | 138.3 | 67.1 | 7.1 |
| 37 | May-16 | 146.8 | 72.6 | 7.5 |
| 38 | Nov-15 | 157.1 | 80.6 | 7.9 |
| 39 | Oct-15 | 151.3 | 76.3 | 8.15 |
| 40 | Aug-15 | 141.6 | 71.2 | 7.8 |
| 41 | Jun-15 | 143.2 | 71.9 | 8.5 |
| 42 | May-15 | 147.9 | 73.45 | 6.44 |
| 43 | Apr-15 | 144.9 | 71.9 | 6.4 |
| 44 | Oct-14 | 158.1 | 77.8 | 7.1 |
| 45 | Sep-14 | 138.1 | 67 | 6.9 |
| 46 | Jul-14 | 139.6 | 69.7 | 7.5 |
| 47 | Jul-14 | 139.2 | 68.5 | 8.9 |
| 48 | Mar-14 | 152.6 | 75 | 9.2 |
| 49 | Sep-13 | 123.8 | 58.6 | 7.6 |
| 50 | Sep-12 | 123.8 | 58.6 | 7.6 |

## A.2 Earbud size

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Length(mm) | Width(mm) | Depth(mm) |
| 1 | 35.8 | 18.9 | 17.7 |
| 2 | 35.9 | 18.5 | 17 |
| 3 | 35.3 | 20.7 | 23.3 |
| 4 | 27.5 | 21.05 | 24.4 |
| 5 | 31.97 | 21.13 | 23.18 |
| 6 | 33 | 22.44 | 21.81 |
| 7 | ‎28.4 | 21.3 | 23.4 |
| 8 | 40 | 30 | 24 |
| 9 | 28.45 | 21.34 | 23.37 |
| 10 | 43.6 | 17.8 | 23.2 |
| 11 | 26 | 29.6 | 21.7 |
| 12 | 29.1 | 21.8 | 23.7 |
| 13 | 38.1 | 20.6 | 20 |
| 14 | 33.66 | 17.83 | 18.13 |
| 15 | 29.1 | 21.8 | 23.7 |
| 16 | 41.5 | 20.4 | 17.8 |
| 17 | 41.4 | 18.5 | 16.8 |
| 18 | 37.5 | 23.9 | 21 |
| 19 | 30.9 | 23.9 | 21.7 |
| 20 | 40.5 | 16.5 | 18 |
| 21 | 30.79 | 18.26 | 19.21 |
| 22 | 33 | 17.4 | 18.4 |
| 23 | 33.2 | 21.9 | 24.9 |
| 24 | 38.82 | 18.6 | 16.81 |
| 25 | 30.9 | 20.9 | 23.5 |
| 26 | 30.5 | 24.3 | 21.6 |
| 27 | 41.8 | 23.7 | 19.8 |
| 28 | 20.9 | 17 | 21.1 |
| 29 | 21.6 | 19.9 | 18.7 |
| 30 | 33.9 | 21.9 | 19.7 |
| 31 | 30.08 | 16.55 | 18.21 |
| 32 | 30.2 | 23.8 | 22.2 |
| 33 | 20.5 | 18.5 | 15 |
| 34 | 30 | 19 | 24 |
| 35 | 28.2 | 19.6 | 18.8 |
| 36 | 22.2 | 23.3 | 16.6 |
| 37 | 23 | 20 | 15 |

## A.3 Tablet size

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Length(mm) | Width(mm) | Depth(mm) |
| 1 | 280.6 | 214.9 | 6.4 |
| 2 | 248.6 | 179.5 | 7 |
| 3 | 195.4 | 134.8 | 6.3 |
| 4 | 247.6 | 178.5 | 6.1 |
| 5 | 289.1 | 196.1 | 5.5 |
| 6 | 261.89 | 178.17 | 6.4 |
| 7 | 246.9 | 156.7 | 7.85 |
| 8 | 260.88 | 176.82 | 6.85 |
| 9 | 253.8 | 165.3 | 6.3 |
| 10 | 326.4 | 208.6 | 5.5 |
| 11 | 253.8 | 165.3 | 6.3 |
| 12 | 246.8 | 161.9 | 6.9 |
| 13 | 291.71 | 191.12 | 6.49 |
| 14 | 267.3 | 167.4 | 6.9 |
| 15 | 252.1 | 163.64 | 7.35 |
| 16 | 277 | 178.95 | 6.99 |
| 17 | 253.95 | 165.18 | 6.51 |
| 18 | 245.08 | 154.84 | 6.94 |
| 19 | 252.2 | 163.8 | 6.99 |
| 20 | 259.73 | 176 | 6.67 |
| 21 | 266.03 | 191.6 | 6.59 |

## A.4 Laptop size

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Length(mm) | Width(mm) | Depth(mm) |
| 1 | 363.4 | 260.25 | 22 |
| 2 | 312 | 221 | 15.99 |
| 3 | 369 | 259.4 | 23.5 |
| 4 | 321.9 | 213.9 | 19.9 |
| 5 | 296.68 | 213.5 | 15.65 |
| 6 | 356.98 | 288.73 | 25.65 |
| 7 | 286.5 | 184.7 | 7.99 |
| 8 | 313.8 | 229.8 | 16.7 |
| 9 | 354.9 | 251.9 | 22.45 |
| 10 | 296.2 | 216.5 | 10.9 |
| 11 | 340.4 | 237.6 | 11.5 |
| 12 | 312.6 | 221.2 | 15.5 |
| 13 | 356 | 247.7 | 20.2 |
| 14 | 315.6 | 222.5 | 14.9 |
| 15 | 364.81 | 289.98 | 18.5 |
| 16 | 410.3 | 319.9 | 26.7 |
| 17 | 296.5 | 205.5 | 12 |
| 18 | 294 | 197 | 8.95 |
| 19 | 305.7 | 199.8 | 12.9 |
| 20 | 359.5 | 238.3 | 15.9 |

## A.5 Watch size

Rectangle type:

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Length(mm) | Width(mm) | Depth(mm) |
| 1 | 45 | 38 | 10.7 |
| 2 | 49 | 44 | 14.4 |
| 3 | 40 | 34 | 10.7 |
| 4 | 53 | 45.7 | 14.7 |
| 5 | 52 | 41 | 14.55 |
| 6 | 50.96 | 42.4 | 14.9 |
| 7 | 57 | 44.5 | 14 |

Circular type:

|  |  |  |
| --- | --- | --- |
| Model | Diameter(mm) | Depth(mm) |
| 1 | 46.5 | 10.9 |
| 2 | 48.5 | 13 |
| 3 | 46 | 13 |

## A.6 AR glass size

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Length(mm) | Width(mm) | Depth(mm) |
| 1 | 167 | 173 | 52 |
| 2 | 179 | 159 | 48 |
| 3 | 152.5 | 159 | 54.7 |
| 4 | 175 | 146 | 44 |
| 5 | 159 | 148 | 52 |
| 6 | 290 | 200 | 57 |

## A.7 Car exterior size

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Length(mm) | Width(mm) | Depth(mm) |
| 1 | 5020 | 1945 | 1760 |
| 2 | 4770 | 1930 | 1625 |
| 3 | 4480 | 1970 | 1601 |
| 4 | 5099 | 1989 | 1750 |
| 5 | 4880 | 1896 | 1450 |
| 6 | 4720 | 2089 | 1442 |
| 7 | 5021 | 1987 | 1478 |
| 8 | 5218 | 1998 | 1800 |
| 9 | 4458 | 1841 | 1632 |
| 10 | 4678 | 1806 | 1474 |
| 11 | 5320 | 1945 | 1488 |

## A.8 Car exterior and interior size

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Model | Exterior | | | Interior | | | | | | | |
| Length (mm) | Width (mm) | Height  (mm) | Head room front(mm) | Head room rear(mm) | Leg room front(mm) | Leg room rear(mm) | Hip room front (mm) | Hip room rear(mm) | Shoulder room front(mm) | Shoulder room rear(mm) |
| 1 | 4648.2 | 1838.96 | 1689.1 | 1043.94 | 1099.82 | 1054.1 | 977.9 | 1374.14 | 1419.86 | 1450.34 | 1419.86 |
| 2 | 4495.8 | 1739.9 | 1460.5 | 1003.3 | 922.02 | 1130.3 | 787.4 | 1292.86 | 1272.54 | 1348.74 | 1361.44 |
| 3 | 4750 | 1921 | 1624 | 1041 | 1001 | 1063 | 1029 | 1367 | 1286 | 1432 | 1372 |
| 4 | 5021 | 1987 | 1431 | 1008 | 968 | 1077 | 901 | 1393 | 1278 | 1484 | 1399 |

# Annex B: Stereo AEC

## B.1 Introduction

In the context of multi-channel AEC, stereo AEC is considered a typical basis, therefore, it takes stereo as an example for AEC algorithm analysis and issue investigation. The stereo AEC is shown in Fig.B-1.

A screenshot of a computer

Description automatically generated

Fig. B.1-1. Stereo AEC system.

The two input signals  and  are derived from the same sound source convolving with two distinct impulse responses  and , so they typically have high correlations. After transmission of the distant stereo signal to the receiving room (near-end) and playback through the loudspeakers, the signals converge through the impulse responses  and of the near-end room to a single microphone, forming the desired signal  together with the noise signal . Subsequently, two adaptive FIR filters  and are employed to estimate the impulse responses  and  of the near-end room, yielding the estimated desired signal . Finally, the difference between the desired signal and the estimated desired signal which termed as the error signal is transmitted back to the distant end. Meanwhile, both the error signal and the input signals contribute to the updates of the adaptive filter coefficients. The following description focuses on a single microphone, and the other microphone follows a similar process.

## B.2 Intuitive understanding of Stereo AEC

As illustrated in Fig. 7.1.3.1-1, assuming is the truncated vector of the actual echo path impulse response in the near-end room, and is the coefficient vector of the FIR filter. We define vector  as the filter misalignment vector. Ideally,

 (1)

The impulse responses of the distant room are denoted as  and , then substitute and into equation (1), and to do Fourier transformation as follows:

 (2)

 and  are the Fourier transforms of and , and  are the Fourier transforms of  and , represents the Fourier transform of the signal source 𝒔. For the single-channel AEC, is zero, so as long as  is not zero at the frequency point of interest, ensuring  to zero enables the filter estimating the path perfectly. However, for stereo AEC,  must not be zero, and  as the distant sound source is not zero either. Hence, we can now simplify (2), giving

 (3)

It can be seen from (3) that it is obviously impossible to deduce the conclusion of and .

### B.2.1 De-correlation based method for stereo AEC

The de-correlation based method is a common solution for stereo AEC, the principles are described in the following.

#### B.2.1.1 Analysis of stereo audio covariance matrix[10]

In practical scenarios, the length of the actual room impulse response is infinite, but the trailing amplitude is generally small, and the effective length of the amplitude is limited. The impulse response length of the far-end room is set as M, the impulse response length of the near-end room is set as N, and the adaptive filter coefficient length is set as L. The error signal at time n between the output signal of the adaptive filter and the desired signal can be expressed as

 (4)

Use recursive least square error formula, giving

 (5)

where ( ) is an exponential forgetting factor. The minimization of (5) leads to the normal equation

 (6)

Where

 (7)

is an estimate of the input signal covariance matrix and

 (8)

is an estimation of the cross-correlation vector between the input and output signals. In this scenario, if  is not full rank, the normal equation does not have a unique solution, and the solution to the adaptive filter convergence may deviate from the actual room impulse response. Here examining the problem in terms of the sizes of the adaptive filter coefficient length (L) and the impulse response length of the distant room (M) so as to consider the uniqueness of the regularization equation solution.

Because the impulse response of the far-end length is infinite, L<M accords with the actual situation. Construct a new vector of length 2L, where  is the truncated vector of , giving

 (9)

where

 (10)

 (11)

Hence, matrix  is non-singular from the perspective of the Wiener solution, and the adaptive filter in stereo AEC has a unique solution, however, due to the relatively small values of  and , the covariance matrix  is very ill-conditioned, exhibiting significant divergence in eigenvalues, resulting in a slow convergence rate of the adaptive filter. This is commonly referred to as the “non-uniqueness” issue in the multi-channel acoustic echo problems. Under the premise of , the misalignment of the solution is considered.

The length L of the adaptive filter is actually smaller than the impulse response length N of the near-end room. The near-end room impulse response  is divided into two parts, one is the vector  matching the first L points of the adaptive filter length, and the other is the trailing vector  with the length of N-L. At the same time, we make repeated supplementary definitions for the input signal to match the room impulse response length. After a series of derivation, the Wiener solution can be got as follows:

 (12)

It can be concluded that the estimated adaptive solution is closely related to  from the point of view of Wiener solution.

#### B.2.1.2 Relationship between channel correlation and condition number of the covariance matrix[11]

From the above description, we can know that the coefficients of the adaptive filter are closely related to the norm of covariance matrix R, and further deduce that the condition number is used to measure the ill-conditioned degree of covariance matrix. The concept of matrix condition number is the product of the norm of the matrix and the norm of its inverse matrix, which is used to express the sensitivity of matrix calculation to error signals. Therefore, we use the condition number to establish the relationship between the correlation of stereo signals and the covariance matrix. Set , and the two-channel covariance matrix is thus given by

 (13)

where  is the mathematical expectation operator, the  is the covariance matrix between the th and th channel. It is noted that for , a Toeplitz matrix is asymptotically equivalent to a circulant matrix if its elements are absolutely summable, giving in (13) as (14)

 (14)

where is the Fourier matrix defined with elements .The matrix contains elements corresponding to the frequency bins, which are formed from the Discrete Fourier Transform (DFT) of the first column of .Letting  be the auto- and cross-correlation coefficients for and , respectively, establishing the relationship between  and  as follows

 (15)

The covariance matrix R of stereo signal can be expressed as

 (16)

In this content, E-norm is used to represent the condition number  of matrix R. The E-norm is equivalent to the F-norm scaled by a factor . Through this transformation, the dependence of conditional number on L is eliminated. After a series of derivation, the condition number under E-norm is obtained as follows

 (17)

Use positive definite covariance matrix to diagonalize to calculate , giving

 (18)

According to (15), We may now see that the square of the inter-channel coherence function at F frequency point can be expressed by the frequency spectrum of the input signal as

 (19)

After a series of derivation, (18) can be further expressed as

 (20)

#### B.2.1.3 Summary de-correlation based method

According to the description, the square of the condition number of covariance matrix R increases with the increase of the inter-channel coherence function , which means that the greater the inter-channel coherence, the greater the condition number of covariance matrix R, the more ill-conditioned matrix R, the greater the sensitivity of matrix calculation to error signals, and the more difficult it is for adaptive filters to solve coefficients. Therefore, in the stereo AEC, de-correlation of channel signals is a key step to the solution of adaptive filter coefficients, but this operation will bring sound quality degradation which may be balanced in this method.

Annex <X> (informative):  
Change history

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Change history** | | | | | | | |
| **Date** | **Meeting** | **TDoc** | **CR** | **Rev** | **Cat** | **Subject/Comment** | **New version** |
| 2023-02 | SA4#122 | S4-230317 |  |  |  | Initial version | V0.0.1 |
| 2023-04 | SA4#123-e | S4-230551 |  |  |  | Updated version based on SA4-post 122 24,March ,2023 | V0.0.2 |
| 2023-04 | SA4#123-e | S4-230646 |  |  |  | Update style and include agreed content in S4-230522 and S4-230523 | V0.0.3 |
| 2023-05 | SA4#124 | S4-230971 |  |  |  | Binaural capture on UE (from S4- 230881) and some online updates in addition | 0.1.0 |
| 2023-07 | SA4#124-Post | S4Aa230088 |  |  |  | Update contents in scope section | 0.1.1 |
| 2023-08 | SA4#125 | S4-231347 |  |  |  | Integrate content based on S4Aa230088 during SA4-e (AH) Audio SWG post 124 31 July 2023. | 0.1.2 |
| 2023-08 | SA4#125 | S4-231496 |  |  |  | Integrate agreed contents of stereo capture principal from S4-231460 | 0.2.0 |
| 2023-11 | SA4#126 | S4-231775 |  |  |  | Integrate agreed content from S4Aa230109 and S4Aa230111 | 0.2.1 |
| 2023-11 | SA4#126 | S4-231944 |  |  |  | Integrate agreed contents from S4-231661, S4-231717 and S4-231850 | 0.3.0 |
| 2024-01 | SA4#127 | S4-240218 |  |  |  | Integrate agreed contents from S4Aa230132 | 0.3.1 |
| 2024-01 | SA4#127 | S4-240358 |  |  |  | Integrated following updates:  contents from S4-240150(two paragraphs) as 6.2.3.5  Contents from S4-240201 as 7.2  Contents from S4-240153 as Annex B  Contents from S4-240243 as 4.1.2  Contents from S4-240241  Integrate S4-240231 in the bracket with editor’s note | 0.4.0 |
| 2024-03 | SA4#127-post | S4aA240014 |  |  |  | Editorial corrections: fixed hanging paragraphs, chapter/ reference number, etc. | 0.4.1 |
| 2024-04 | SA4#127-bis-e | S4-240740 |  |  |  | Integrated following updates:  Agreed contents from S4aA240015  Agreed contents from S4aA240014 | 0.5.0 |
| 2024-04 | SA4#127-bis-e | S4-240764 |  |  |  | Integrated following updates:  1:Agreed contents from S4-240731  2:Agreed contents from S4-240733  3:Section 2 from S4-240665 in bracket for further discussion | 0.6.0 |
| 2024-05 | SA4#128 | S4-241038 |  |  |  | Editorial updates and remove bracket for the completed parts | 0.6.1 |
| 2024-05 | SA4#128 | S4-241173 |  |  |  | Integrated the following contents:  1:Agreed contents from S4-241192  2:Agreed contents from S4-241038  3:Agreed contents from S4-241039 in brackets | 0.7.0 |
| 2024-06 |  |  |  |  |  | Version 1.0.0 created by MCC, presentation for information to TSG | 1.0.0 |
| 2024-06 | [3GPPSA4-e (AH) Audio SWG post 128](https://portal.3gpp.org/Home.aspx" \l "/meeting?MtgId=60700) | SA4aA240044 |  |  |  | Remove automatic-numbering and some other editorial updates | 1.0.1 |
| 2024-08 | SA4#129-e | S4-241524 |  |  |  | Some editorial updates and integrating contents from SA4aA240040, SA4aA240042, SA4aA240043, SA4aA240045. | 1.0.2 |
| 2024-08 | SA4#129-e | S4-241666 |  |  |  | Integrated agreed contents from S4-241511 and change from “microphone design for UEs” to “microphone integration in UEs” in clause 7.  Integrated agreed contents “2.2 Proposed updates in clause 7.2.4.3 HOA” from S4-241511 and made reference for third solution with IVAS.  Remove 2 editor’s note.  Replace “should” by”may” | 1.1.0 |