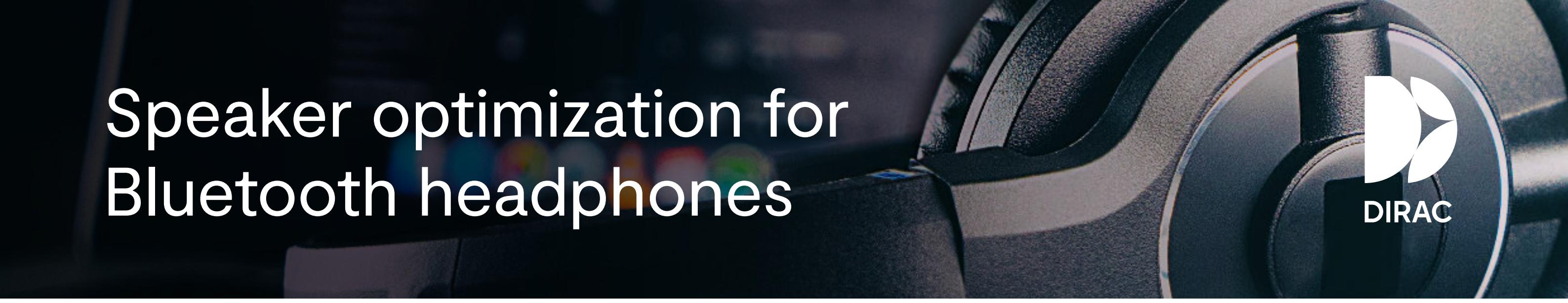


Speaker optimization for Bluetooth headphones

Executive summary

Headphone manufacturers strive to consistently attain the signature sound that their customers love. This white paper shares the main insights from Dirac's patented recipe to always and timely reach the maximum potential of the headphones: A robust semi-automatic sound quality optimization technology, leveraging high-resolution acoustical measurements and data-processing and a software-only embedded solution. This sound quality optimization technology is packaged into Dirac Opteo™ and™ Dirac Virtuo™ for Bluetooth headphones.

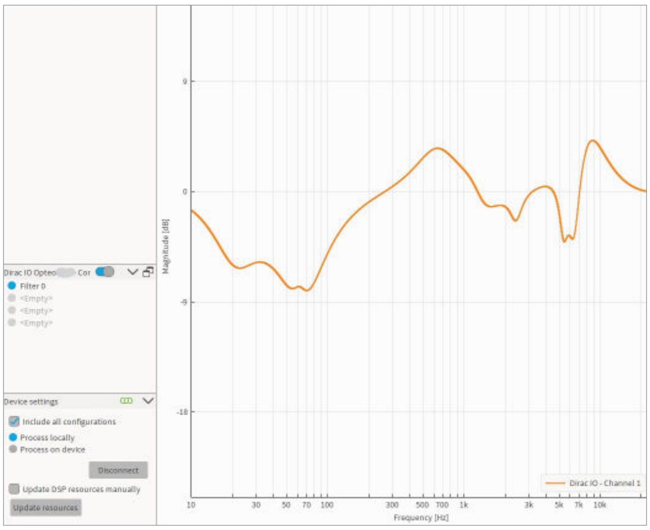
Problem description

According to Qualcomm's report "The State of Sound 2021"[1], sound quality has for six years in a row been the number one purchase driver for consumers' choice of wireless headphones. According to the same report, music listening is the most common usage.

Headphones are electro-acoustical systems with physical constraints implied by product design choices such as type, features, and size. These design choices are not always aimed at delivering the best possible sound, but instead at providing a loveable product with regards to feature set and usability. With sound quality being the number one purchase driver for consumers' choice of wireless headphones, as they are ultimately looking to transparently experience the intent of an artist, an effective and efficient solution is required to also attaining that perfect sound.

Fundamental sound quality issues on headphones include, but are not limited to:

- Bass being too weak or uneven
- Low midrange being either boxy or hollow
- High midrange being either harsh or hollow
- Highs having annoying resonances



Automatically optimized speaker correction filter response

In addition, some sound quality challenges are typical for wireless headphones:

- Distorted soundstage due to asymmetrical placement of components and user controls
- Different ANC modes introducing undesired variability to the sound character

These issues all get in the way of providing a transparent channel from the artist to the consumer. Fortunately, they can all be addressed by a properly designed set of linear filters applied to each of the earpieces.

Different Bluetooth headphone chipset DSPs provide different means for implementing such corrective measures. It is however not straightforward to timely and robustly configure an effective correction that

- removes the obvious issues without over-compensating and causing new issues and
- attains that signature sound that customers recognize and love.

Finally, an efficient implementation is necessary for making the best use of the limited resources and maximise single-charge battery life. Sound quality is after all attributable also to other features, such as source content resolution, Bluetooth codec, ANC, and personalization settings, all of which need to fit within the resource budget. Clearly, an automated data-driven process is preferred.

The solution

Dirac's goal with headphone optimization is to establish a transparent audio channel, so that the intended experience is effortlessly delivered from the artist to the user. To reach this goal, we use a semi-automatic measurement-based filter design methodology based on 20+ years of experience from room correction and headphone compensation.

The fundaments for consistently and timely reaching an effective result are:

A reliable measurement process	Capture the data that accurately represents the headphones' acoustical properties to clearly expose the problems that need to be solved
A robust automatic filter design	Instantly and effectively address the identified relevant problems with adequate precision
A consistent and sensible target sound	Only minor customizations to attain a reproducible OEM signature sound
An efficient DSP implementation	Reach the desired sound with minimum impact on battery life

[1] "The State of Sound Report 2021 – A global analysis of audio consumer behaviors and desires", Qualcomm Technologies, Inc.

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Manual trial-and-error approaches, or simply relying on individual golden ears, while having different capabilities on different chipsets, will lead to unreliable or inconsistent results. Dirac's approach timely provides optimal and objectively verifiable results. In the following sections we detail key functions and share some practical and valuable insights.

How it works

Reliable acoustical measurements

There are many systems available for measuring headphones. At Dirac we have come to value robustness and accuracy because it provides the most useful foundation for our further data processing, which is key to consistently managing the sound quality. Aspects that contribute to robustness and accuracy:

- The right fit for all types of headphones: in-ears, on-ears, and over-ears
- Accurate simulation of outer ear including both the pinna and the ear canal
- Accurate measurement of the whole audible frequency range

GRAS 45CA-9 Headphone Test Fixture

This has led us to lean on GRAS 45CA-9:

- It can be used for all types of headphones, avoiding introduction of systematic errors from using different rigs for different headphone types.
- With a natural-shaped two-ear design and representative pinnae and ear canals, it is possible to measure both earpieces at the same time while also applying the right pressure from the headband itself for over-ear and on-ear headphones.
- It complies with standards (IEC 60318-4) for accurately measuring all types of headphones all the way to 20kHz, eliminating guesswork in the full-band headphone modelling.

Dirac's measurement process is engineered to tolerate normal variations in production quality and user fitting while adequately addressing outliers. Among other things, we also identify systematic left/right asymmetries and different ANC modes to ensure capturing all aspects that may require special attention.

Model design

All headphone measurements are converted into high-resolution impulse response models to ensure proper capture of both magnitude and phase properties.

Recent research indicates that we can hear phase distortion if it exceeds a certain threshold.[2] However, most headphones are minimum-phase systems and we always verify this. For most headphones, we only need to ensure that the applied magnitude response correction doesn't contribute to crossing that threshold. Therefore, it's highly relevant to work with the complete impulse response models.

In the rare case that non-minimum-phase properties are part of the problem, then Dirac® can leverage the mixed-phase correction technology used in Dirac Live® for loudspeaker systems in homes, studios, cinemas, and cars.

Automatic filter design

The automatic optimization of the compensation filters will attain the desired magnitude response of the filter & headphone combined system, including variants due to asymmetry and ANC modes. The steps to get there include:

- Target response design
- Introduction of filter design criteria and trade-offs
- Choice of filter type and corresponding coefficient calculation
- Validation of implementation on hardware

Minimum-phase and non-minimum-phase

A minimum-phase system has the least energy delay of all systems with a specific magnitude response.
Any system can be factored into a minimum-phase part and an all-pass part. If the all-pass part is not a unit impulse, then the system is non-minimum-phase.
For more insight into the differences between minimum-phase and non-minimum-phase systems and compensation filter properties, capabilities, and applicability, please refer to the white paper **"ON ROOM CORRECTION AND EQUALIZATION OF SOUND SYSTEMS"** by Dr Mathias Johansson.

[2] Audibility of Group-Delay Equalization; Juho Liski, Aki Mäkivirta, and Vesa Välimäki; IEEE/ACM TRANSACTIONS ON AUDIO, SPEECH, AND LANGUAGE PROCESSING, VOL. 29, 2021

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Target response design

Dirac's goal is to effortlessly deliver the intended experience from the artist to the user. To understand the implication of this goal on headphone optimization, it is important to acknowledge that in most content production studios, reference loudspeakers are used for validating the experience. Therefore, Dirac's principle for target response design in headphone optimization is to make up for two contributions that normally get lost when using headphones:

A) the room gain below 200 Hz of a pair of speakers in a room and

B) the pinna coloration above 1 kHz pertaining to the speakers being placed in front of the listener.

The same guiding principle applies to the Dirac Virtuo stereo spatialization, but with the addition of virtual room dimensions to externalize the soundstage in front of the listener.

The target curve will undergo some customization when optimizing a headphone for attaining an OEM's signature sound.

Measurement equipment and magnitude targets

The result of the measurements, and consequently, the definition of a headphone's target sound character, highly depends on the measurement equipment. So, when discussing or comparing magnitude target responses in detail, one must relate it also to the equipment used to attain or verify that response.

Introducing design criteria and trade-offs

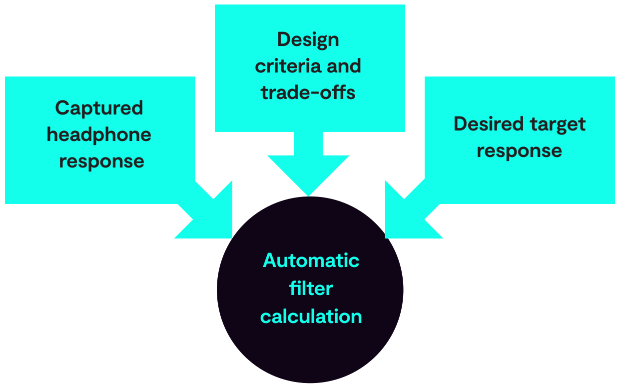
Based on the captured headphone models and the desired target response, the optimum set of filters can be calculated.

Design criteria and trade-offs are introduced to the otherwise automatic filter design, such as

- the maximum allowed gain the filter may apply at different frequency regions, and
- how the filter should behave at the extremes of the frequency spectrum.

Automatic optimization has clear advantages over a manual approach:

- The magnitude and phase distortions may require very intricate combinations of filter types and parameter settings to be properly corrected.



- Hardware design cycles may require this process to be repeated several times in a product project.
- It's easy to get lost in why specific settings have been made unless they are introduced as constraints with a purpose.
- A computer algorithm fed with data based on measurements and design criteria is simply better and faster at finding the filter coefficients that best attain the desired sound.

Speaker optimization for Bluetooth headphones

Fine tuning

Until this point, the process from measurement to filter design has been mostly automatic. Subjective evaluation is done while allowing for fine manual adjustments of the magnitude response, assisted by visual representation of the headphone's objective acoustical data.

One potential remaining aspect that has not been revealed by the measurements is the presence and severity of ear-canal resonances. Ear-canal resonances arise from an interaction between the headphone driver and the sealed space between the eardrum and the headphone. The exact resonance characteristics depend on the dimensions of the ear-canal and on the type of headphone. During the fine tuning, the ear-canal resonance correction filter will be identified and generalized to

- compensate for what would be perceivable by most people, while
- making a sufficient but not exaggerated compensation.

Digital filter implementation on Bluetooth chipset

The compensation filters are intermediately designed as long FIR (finite impulse response) filters of very high frequency- and time resolution, ensuring that precise and accurate correction of the identified distortions are carried through all design steps.

However, this filter structure is not suitable for a battery-powered DSP, such as those in Bluetooth chipsets. As a final critical step in the filter design process, the compensation filter is realized and validated on the target DSP.

Due to the fact that most headphones can be properly corrected by a minimum-phase filter, it is in these cases sufficient with a cascade of second-order IIR (infinite impulse response) filters to most effectively realize the necessary correction filter. Minimum-phase filters also provide the lowest possible processing latency of all filter types. The exact arithmetical implementation is chosen to make the best use of the chipset's DSP architecture.

In the rare cases that a mixed-phase filter is required, we implement the filter as a so-called FIIR filter, which is a hybrid filter structure consisting of a short FIR filter and a set of second-order IIR filters, all in parallel.

Conclusion

The speaker optimization used in Dirac Opteo™ and Dirac Virtuo™ for Bluetooth headphones, provides a means for timely and reproducibly optimizing the sound quality on a pair of wireless headphones. The semi-automatic process covers all steps from measurement of the headphones, through high-resolution digital filter design, to an efficient implementation of the correction filter on the embedded DSP. It helps headphone OEMs attain their desired signature sound – on time and on target.

About Dirac

Dirac is here to change the world of sound. We're inventing the future of audio with superior experiences for any content, device, and space. For the many, not the few. Based in Sweden, Dirac optimizes digital audio, perfecting sound for better listening in any environment. The patented sound solution technology spans across mobile, gaming, Virtual Reality and Augmented Reality, headphones, streaming, automotive, residential and commercial AV, boosting whatever sound you're listening to, wherever you're listening. For professionals, Dirac produces the industry's most powerful suite of audio tools for signal processing. Some of the world's most respected brands, including Rolls Royce, Volvo, Polestar, BMW, BYD, Harman, Datasat, NAD, ASUS, and OPPO bring the Dirac sound experience to their customers.

Dirac is a global company with headquarters in Uppsala, Sweden and R&D facilities in Copenhagen, Denmark and Bangalore, India, with representation in China, Germany, Japan, Korea, Taiwan and USA.