Office de la Propriété Intellectuelle du Canada
Un organisme d'Industrie Canada

Canadian Intellectual Property Office
An agency of Industry Canada

CA 2924700 A1 2015/04/30

(21) **2 924 700**

(12) DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION

(13) **A1**

(86) **Date de dépôt PCT/PCT Filing Date:** 2014/10/20
(87) **Date publication PCT/PCT Publication Date:** 2015/04/30
(85) **Entrée phase nationale/National Entry:** 2016/03/16
(86) **N° demande PCT/PCT Application No.:** EP 2014/072411
(87) **N° publication PCT/PCT Publication No.:** 2015/059081
(30) **Priorité/Priority:** 2013/10/23 (EP13290255.2)

(51) **Cl.Int./Int.Cl.** ***H04S 3/02*** (2006.01)
(71) **Demandeur/Applicant:**
THOMSON LICENSING, FR

(72) **Inventeurs/Inventors:**
KEILER, FLORIAN, DE;
BOEHM, JOHANNES, DE

(74) **Agent:** FETHERSTONHAUGH & CO.

(54) **Titre : PROCEDE ET APPAREIL DE DECODAGE DE REPRESENTATION DE CHAMP ACOUSTIQUE A AUDIO AMBIOPHONIQUE POUR LA LECTURE AUDIO UTILISANT DES CONFIGURATIONS 2D**
(54) **Title: METHOD FOR AND APPARATUS FOR DECODING AN AMBISONICS AUDIO SOUNDFIELD REPRESENTATION FOR AUDIO PLAYBACK USING 2D SETUPS**

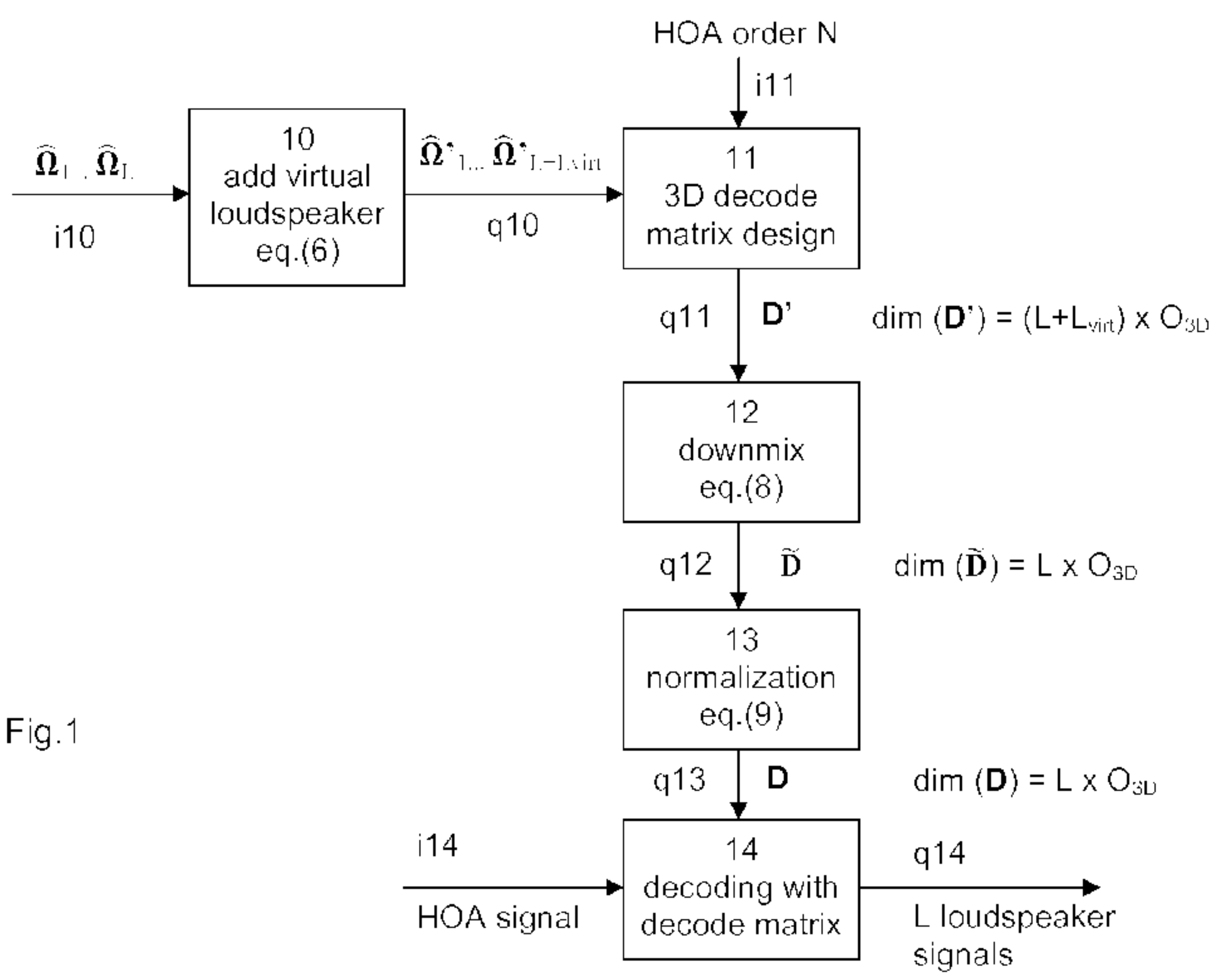


Fig.1

$$(\hat{\Omega}_1 \ldots \hat{\Omega}_L) \quad \text{(I)}$$

$$(\hat{\Omega}'_{L+1}) \quad \text{(II)}$$

$$(\tilde{D}) \quad \text{(III)}$$

(57) **Abrégé/Abstract:**
Sound scenes in 3D can be synthesized or captured as a natural sound field. For decoding, a decode matrix is required that is specific for a given loudspeaker setup and is generated using the known loudspeaker positions. However, some source directions

(57) **Abrégé(suite)/Abstract(continued):**
are attenuated for 2D loudspeaker setups like e.g. 5.1 surround. An improved method for decoding an encoded audio signal in soundfield format for L loudspeakers at known positions comprises steps of adding (10) a position of at least one virtual loudspeaker to the positions of the L loudspeakers, generating (11) a 3D decode matrix (D'), wherein the positions (Formula I) of the L loudspeakers and the at least one virtual position (Formula II) are used, downmixing (12) the 3D decode matrix (D'), and decoding (14) the encoded audio signal (i14) using the downscaled 3D decode matrix (Formula III). As a result, a plurality of decoded loudspeaker signals (q14) is obtained.

CA 02924700 2016-03-16

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
30 April 2015 (30.04.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/059081 A1

(51) International Patent Classification: *H04S 3/02* (2006.01)

(21) International Application Number: PCT/EP2014/072411

(22) International Filing Date: 20 October 2014 (20.10.2014)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
13290255.2 23 October 2013 (23.10.2013) EP

(71) Applicant: **THOMSON LICENSING** [FR/FR]; 1-5 rue Jeanne d'Arc, F-92130 Issy-les-Moulineaux (FR).

(72) Inventors: **KEILER, Florian**; Kleine Pfahlstrasse 20, 30161 Hannover (DE). **BOEHM, Johannes**; Sieberweg 35, 37081 Göttingen (DE).

(74) Agent: **KÖNIG, Uwe**; Deutsche Thomson OHG, European Patent Operations, Karl-Wiechert-Allee 74, 30625 Hannover (DE).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

(54) Title: METHOD FOR AND APPARATUS FOR DECODING AN AMBISONICS AUDIO SOUNDFIELD REPRESENTATION FOR AUDIO PLAYBACK USING 2D SETUPS

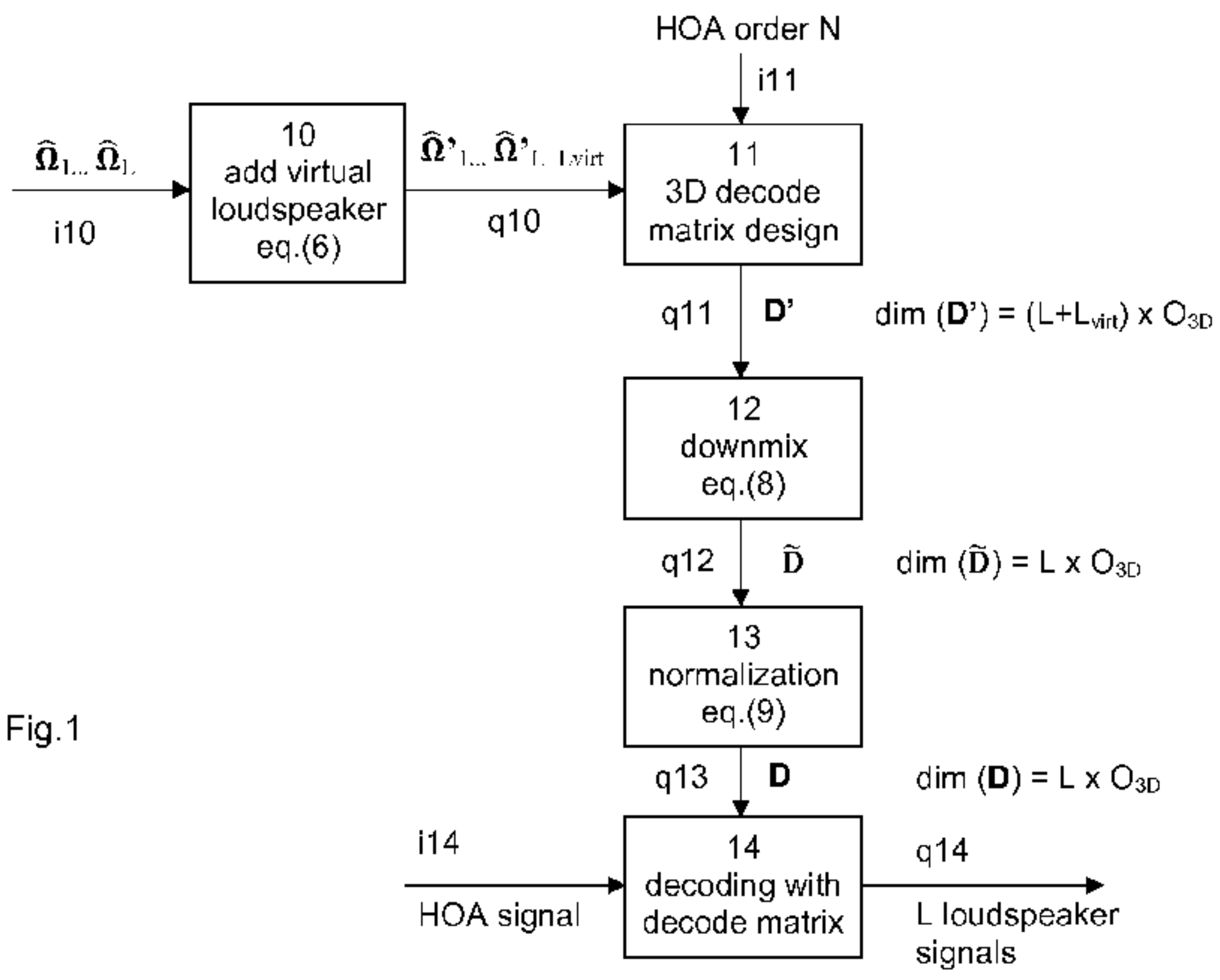


Fig.1

(57) Abstract: Sound scenes in 3D can be synthesized or captured as a natural sound field. For decoding, a decode matrix is required that is specific for a given loudspeaker setup and is generated using the known loudspeaker positions. However, some source directions are attenuated for 2D loudspeaker setups like e.g. 5.1 surround. An improved method for decoding an encoded audio signal in soundfield format for L loudspeakers at known positions comprises steps of adding (10) a position of at least one virtual loudspeaker to the positions of the L loudspeakers, generating (11) a 3D decode matrix (*D'*), wherein the positions (Formula I) of the L loudspeakers and the at least one virtual position (Formula II) are used, downmixing (12) the 3D decode matrix (*D'*), and decoding (14) the encoded audio signal (i14) using the downscaled 3D decode matrix (Formula III). As a result, a plurality of decoded loudspeaker signals (q14) is obtained.

$$(\hat{\Omega}_1 \dots \hat{\Omega}_L) \quad \text{(I)}$$

$$(\hat{\Omega}'_{L+1}) \quad \text{(II)}$$

$$(\tilde{D}) \quad \text{(III)}$$

WO 2015/059081 A1

METHOD FOR AND APPARATUS FOR DECODING AN AMBISONICS AUDIO SOUNDFIELD REPRESENTATION FOR AUDIO PLAYBACK USING 2D SETUPS

Field of the invention

This invention relates to a method and an apparatus for decoding an audio soundfield representation, and in particular an Ambisonics formatted audio representation, for audio playback using a 2D or near-2D setup.

Background

Accurate localization is a key goal for any spatial audio reproduction system. Such reproduction systems are highly applicable for conference systems, games, or other virtual environments that benefit from 3D sound. Sound scenes in 3D can be synthesized or captured as a natural sound field. Soundfield signals such as e.g. Ambisonics carry a representation of a desired sound field. A decoding process is required to obtain the individual loudspeaker signals from a sound field representation. Decoding an Ambisonics formatted signal is also referred to as “rendering”. In order to synthesize audio scenes, panning functions that refer to the spatial loudspeaker arrangement are required for obtaining a spatial localization of the given sound source. For recording a natural sound field, microphone arrays are required to capture the spatial information. The Ambisonics approach is a very suitable tool to accomplish this. Ambisonics formatted signals carry a representation of the desired sound field, based on spherical harmonic decomposition of the soundfield. While the basic Ambisonics format or B-format uses spherical harmonics of order zero and one, the so-called Higher Order Ambisonics (HOA) uses also further spherical harmonics of at least 2nd order. The spatial arrangement of loudspeakers is referred to as loudspeaker setup. For the decoding process, a decode matrix (also called rendering matrix) is required, which is specific for a given loudspeaker setup and which is generated using the known loudspeaker positions.

Commonly used loudspeaker setups are the stereo setup that employs two loudspeakers, the standard surround setup that uses five loudspeakers, and extensions of the surround setup that use more than five loudspeakers. However, these well-known setups are restricted to two dimensions (2D), e.g. no height information is reproduced. Rendering for known loudspeaker setups that can reproduce height information has disadvantages in sound localization and coloration: either spatial vertical pans are perceived with very uneven loudness, or loudspeaker signals have strong side lobes, which is disadvantageous especially for off-center listening positions. Therefore, a so-called energy-preserving rendering design is preferred when rendering a HOA sound field description to loudspeakers. This means that rendering of a single sound source results in loudspeaker signals of constant energy, independent of the direction of the source. In other words, the input energy carried by the Ambisonics representation is preserved by the loudspeaker renderer. The International patent publication WO2014/012945A1 [1] from the present inventors describes a HOA renderer design with good energy preserving and localization properties for 3D loudspeaker setups. However, while this approach works quite well for 3D loudspeaker setups that cover all directions, some source directions are attenuated for 2D loudspeaker setups (like e.g. 5.1 surround). This applies especially for directions where no loudspeakers are placed, e.g. from the top.

In F. Zotter and M. Frank, “All-Round Ambisonic Panning and Decoding” [2], an “imaginary” loudspeaker is added if there is a hole in the convex hull built by the loudspeakers. However, the resulting signal for that imaginary loudspeaker is omitted for playback on the real loudspeaker. Thus, a source signal from that direction (i.e. a direction where no real loudspeaker is positioned) will still be attenuated. Furthermore, that paper shows the use of the imaginary loudspeaker for use with VBAP (vector base amplitude panning) only.

Summary of the Invention

Therefore, it is a remaining problem to design energy-preserving Ambisonics renderers for 2D (2-dimensional) loudspeaker setups, wherein sound sources from directions where no loudspeakers are placed are less attenuated or not attenuated at all. 2D loudspeaker setups can be classified as those where the loudspeakers' elevation angles are within a defined small range (e.g. <10°), so that they are close to the horizontal plane.

The present specification describes a solution for rendering/decoding an Ambisonics formatted audio soundfield representation for regular or non-regular spatial loudspeaker distributions, wherein the rendering/decoding provides highly improved localization and coloration properties and is energy preserving, and wherein even sound from directions in which no loudspeaker is available is rendered. Advantageously, sound from directions in which no loudspeaker is available is rendered with substantially the same energy and perceived loudness that it would have if a loudspeaker was available in the respective direction. Of course, an exact localization of these sound sources is not possible since no loudspeaker is available in its direction.

In particular, at least some described embodiments provide a new way to obtain the decode matrix for decoding sound field data in HOA format. Since at least the HOA format describes a sound field that is not directly related to loudspeaker positions, and since loudspeaker signals to be obtained are necessarily in a channel-based audio format, the decoding of HOA signals is always tightly related to rendering the audio signal. In principle, the same applies also to other audio soundfield formats. Therefore the present disclosure relates to both decoding and rendering sound field related audio formats. The terms decode matrix and rendering matrix are used as synonyms.

To obtain a decode matrix for a given setup with good energy preserving properties, one or more virtual loudspeakers are added at positions where no loudspeaker is available. For example, for obtaining an improved decode matrix for a 2D setup, two virtual loudspeakers are added at the top and bottom (corresponding to elevation angles +90° and -90°, with the 2D loudspeakers placed approximately at an elevation of 0°). For this virtual 3D loudspeaker setup, a decode matrix is designed that satisfies the energy preserving property. Finally, weighting factors from the decode matrix for the virtual loudspeakers are mixed with constant gains to the real loudspeakers of the 2D setup.

According to one embodiment, a decode matrix (or rendering matrix) for rendering or decoding an audio signal in Ambisonics format to a given set of loudspeakers is generated by generating a first preliminary decode matrix using a conventional method and using modified loudspeaker positions, wherein the modified loudspeaker positions include loudspeaker positions of the given set of loudspeakers and at least one additional virtual loudspeaker position, and downmixing the first preliminary decode matrix, wherein coefficients relating to the at least one additional virtual loudspeaker are removed and distributed to coefficients relating to the loudspeakers of the given set of loudspeakers. In one embodiment, a subsequent step of normalizing the decode matrix follows. The resulting decode matrix is suitable for rendering or decoding the Ambisonics signal to the given set of loudspeakers, wherein even sound from positions where no loudspeaker is present is reproduced with correct signal energy. This is due to the construction of the improved decode matrix. Preferably, the first preliminary decode matrix is energy-preserving.

In one embodiment, the decode matrix has L rows and O_{3D} columns. The number of rows corresponds to the number of loudspeakers in the 2D loudspeaker setup, and the number of columns corresponds to the number of Ambisonics coefficients O_{3D}, which depends on the HOA order N according to $O_{3D} = (N+1)^2$. Each of the coefficients of the decode matrix for a 2D loudspeaker setup is a sum of at least a first intermediate coefficient and a second intermediate coefficient. The first intermediate coefficient is obtained by an energy-preserving 3D matrix design method for the current loudspeaker position of the 2D loudspeaker setup, wherein the energy-preserving 3D matrix design method uses at least one virtual loudspeaker position. The second intermediate coefficient is obtained by a coefficient that is obtained from said energy-preserving 3D matrix design method for the at least one virtual loudspeaker position, multiplied with a weighting factor g. In one embodiment, the weighting factor g is calculated according to $g = \frac{1}{\sqrt{L}}$, wherein L is the number of loudspeakers in the 2D loudspeaker setup.

In one embodiment, the invention relates to a computer readable storage medium having stored thereon executable instructions to cause a computer to perform a method comprising steps of the method disclosed above or in the claims.
An apparatus that utilizes the method is disclosed in claim 9.

Advantageous embodiments are disclosed in the dependent claims, the following description and the figures.

Brief description of the drawings

Exemplary embodiments of the invention are described with reference to the accompanying drawings, which show in
Fig.1 a flow-chart of a method according to one embodiment;
Fig.2 exemplary construction of a downmixed HOA decode matrix;
Fig.3 a flow-chart for obtaining and modifying loudspeaker positions;
Fig.4 a block diagram of an apparatus according to one embodiment;
Fig.5 energy distribution resulting from a conventional decode matrix;
Fig.6 energy distribution resulting from a decode matrix according to embodiments; and
Fig.7 usage of separately optimized decode matrices for different frequency bands.

Detailed description of embodiments

Fig.1 shows a flow-chart of a method for decoding an audio signal, in particular a soundfield signal, according to one embodiment. The decoding of soundfield signals generally requires positions of the loudspeakers to which the audio signal shall be rendered. Such loudspeaker positions $\hat{\Omega}_1 \ldots \hat{\Omega}_L$ for L loudspeakers are input i10 to the process. Note that when positions are mentioned, actually spatial directions are meant herein, i.e. positions of loudspeakers are defined by their inclination angles θ_l and azimuth angles ϕ_l, which are combined into a vector $\widehat{\mathbf{\Omega}}_l = [\theta_l, \phi_l]^T$. Then, at least one position of a virtual loudspeaker is added 10. In one embodiment, all loudspeaker positions that are input to the process i10 are substantially in the same plane, so that they constitute a 2D setup, and the at least one virtual loudspeaker that is added is outside this plane. In one particularly advantageous embodiment, all loudspeaker positions that are input to the process i10 are substantially in the same plane and the positions of two virtual loudspeakers are added in step 10. Advantageous positions of the two virtual loudspeakers are described below. In one embodiment, the addition is performed according to Eq.(6) below. The adding step 10 results in a modified set of loudspeaker angles $\widehat{\mathbf{\Omega}}'_1 \dots \widehat{\mathbf{\Omega}}'_{L+L_{virt}}$ at q10. L_{virt} is the number of virtual loudspeakers. The modified set of loudspeaker angles is used in a 3D decode matrix design step 11. Also the HOA order N (generally the order of coefficients of the soundfield signal) needs to be provided i11 to the step 11.

The 3D decode matrix design step 11 performs any known method for generating a 3D decode matrix. Preferably the 3D decode matrix is suitable for an energy-preserving type of decoding/rendering. For example, the method described in PCT/EP2013/065034 can be used. The 3D decode matrix design step 11 results in a decode matrix or rendering matrix ***D'*** that is suitable for rendering L' = L + L_{virt} loudspeaker signals, with L_{virt} being the number of virtual loudspeaker positions that were added in the “virtual loudspeaker position adding” step 10.

Since only L loudspeakers are physically available, the decode matrix ***D'*** that results from the 3D decode matrix design step 11 needs to be adapted to the L loudspeakers in a downmix step 12. This step performs downmixing of the decode matrix ***D'*** , wherein coefficients relating to the virtual loudspeakers are weighted and distributed to the coefficients relating to the existing loudspeakers. Preferably, coefficients of any particular HOA order (i.e. column of the decode matrix ***D'***) are weighted and added to the coefficients of the same HOA order (i.e. the same column of the decode matrix ***D'***). One example is a downmixing according to Eq.(8) below. The downmixing step 12 results in a downmixed 3D decode matrix $\widetilde{\boldsymbol{D}}$ that has L rows, i.e. less rows than the decode matrix ***D'***, but has the same number of columns as the decode matrix ***D'***. In other words, the dimension of the decode matrix ***D'*** is ($L+L_{virt}$) x O_{3D}, and the dimension of the downmixed 3D decode matrix $\widetilde{\boldsymbol{D}}$ is L x O_{3D}.

Fig.2 shows an exemplarily construction of a downmixed HOA decode matrix $\widetilde{\boldsymbol{D}}$ from a HOA decode matrix $\boldsymbol{D}'$. The HOA decode matrix $\boldsymbol{D}'$ has L+2 rows, which means that two virtual loudspeaker positions have been added to the L available loudspeaker positions, and O_{3D} columns, with $O_{3D} = (N+1)^2$ and N being the HOA order. In the downmixing step 12, the coefficients of rows L+1 and L+2 of the HOA decode matrix $\boldsymbol{D}'$ are weighted and distributed to the coefficients of their respective column, and the rows L+1 and L+2 are removed. For example, the first coefficients $d'_{L+1,1}$ and $d'_{L+2,1}$ of each of the rows L+1 and L+2 are weighted and added to the first coefficients of each remaining row, such as $d'_{1,1}$. The resulting coefficient $\tilde{d}_{1,1}$ of the downmixed HOA decode matrix $\widetilde{\boldsymbol{D}}$ is a function of $d'_{1,1}$, $d'_{L+1,1}$, $d'_{L+2,1}$ and the weighting factor g. In the same manner, e.g. the resulting coefficient $\tilde{d}_{2,1}$ of the downmixed HOA decode matrix $\widetilde{\boldsymbol{D}}$ is a function of $d'_{2,1}$, $d'_{L+1,1}$, $d'_{L+2,1}$ and the weighting factor g, and the resulting coefficient $\tilde{d}_{1,2}$ of the downmixed HOA decode matrix $\widetilde{\boldsymbol{D}}$ is a function of $d'_{1,2}$, $d'_{L+1,2}$, $d'_{L+2,2}$ and the weighting factor g.

Usually, the downmixed HOA decode matrix $\widetilde{\boldsymbol{D}}$ will be normalized in a normalization step 13. However, this step 13 is optional since also a non-normalized decode matrix could be used for decoding a soundfield signal. In one embodiment, the downmixed HOA decode matrix $\widetilde{\boldsymbol{D}}$ is normalized according to Eq.(9) below. The normalization step 13 results in a normalized downmixed HOA decode matrix $\boldsymbol{D}$, which has the same dimension L x O_{3D} as the downmixed HOA decode matrix $\widetilde{\boldsymbol{D}}$.

The normalized downmixed HOA decode matrix $\boldsymbol{D}$ can then be used in a soundfield decoding step 14, where an input soundfield signal i14 is decoded to L loudspeaker signals q14. Usually the normalized downmixed HOA decode matrix $\boldsymbol{D}$ needs not be modified until the loudspeaker setup is modified. Therefore, in one embodiment the normalized downmixed HOA decode matrix $\boldsymbol{D}$ is stored in a decode matrix storage.

Fig.3 shows details of how, in an embodiment, the loudspeaker positions are obtained and modified. This embodiment comprises steps of determining 101 positions $\widehat{\boldsymbol{\Omega}}_1 \dots \widehat{\boldsymbol{\Omega}}_L$ of the L loudspeakers and an order N of coefficients of the soundfield signal, determining 102 from the positions that the L loudspeakers are substantially in a 2D plane, and generating 103 at least one virtual position $\widehat{\boldsymbol{\Omega}}'_{L+1}$ of a virtual loudspeaker.
In one embodiment, the at least one virtual position $\widehat{\boldsymbol{\Omega}}'_{L+1}$ is one of $\widehat{\boldsymbol{\Omega}}'_{L+1} = [0,0]^T$ and $\widehat{\boldsymbol{\Omega}}'_{L+1} = [\pi, 0]^T$.
In one embodiment, two virtual positions $\widehat{\boldsymbol{\Omega}}'_{L+1}$ and $\widehat{\boldsymbol{\Omega}}'_{L+2}$ corresponding to two virtual loudspeakers are generated 103, with $\widehat{\boldsymbol{\Omega}}'_{L+1} = [0,0]^T$ and $\widehat{\boldsymbol{\Omega}}'_{L+2} = [\pi, 0]^T$.

According to one embodiment, a method for decoding an encoded audio signal for L loudspeakers at known positions comprises steps of determining 101 positions $\hat{\mathbf{\Omega}}_1 \dots \hat{\mathbf{\Omega}}_L$ of the L loudspeakers and an order N of coefficients of the soundfield signal, determining 102 from the positions that the L loudspeakers are substantially in a 2D plane, generating 103 at least one virtual position $\hat{\mathbf{\Omega}}'_{L+1}$ of a virtual loudspeaker, generating 11 a 3D decode matrix ***D'***, wherein the determined positions $\hat{\mathbf{\Omega}}_1 \dots \hat{\mathbf{\Omega}}_L$ of the L loudspeakers and the at least one virtual position $\hat{\mathbf{\Omega}}'_{L+1}$ are used and the 3D decode matrix ***D'*** has coefficients for said determined and virtual loudspeaker positions, downmixing 12 the 3D decode matrix ***D'***, wherein the coefficients for the virtual loudspeaker positions are weighted and distributed to coefficients relating to the determined loudspeaker positions, and wherein a downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$ is obtained having coefficients for the determined loudspeaker positions, and decoding 14 the encoded audio signal i14 using the downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$, wherein a plurality of decoded loudspeaker signals q14 is obtained.

In one embodiment, the encoded audio signal is a soundfield signal, e.g. in HOA format. In one embodiment, the at least one virtual position $\hat{\mathbf{\Omega}}'_{L+1}$ of a virtual loudspeaker is one of $\hat{\mathbf{\Omega}}'_{L+1} = [0,0]^T$ and $\hat{\mathbf{\Omega}}'_{L+1} = [\pi, 0]^T$.
In one embodiment, the coefficients for the virtual loudspeaker positions are weighted with a weighting factor $g = \frac{1}{\sqrt{L}}$.
In one embodiment, the method has an additional step of normalizing the downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$, wherein a normalized downscaled 3D decode matrix ***D*** is obtained, and the step of decoding 14 the encoded audio signal i14 uses the normalized downscaled 3D decode matrix ***D***. In one embodiment, the method has an additional step of storing the downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$ or the normalized downmixed HOA decode matrix ***D*** in a decode matrix storage.

According to one embodiment, a decode matrix for rendering or decoding a soundfield signal to a given set of loudspeakers is generated by generating a first preliminary decode matrix using a conventional method and using modified loudspeaker positions, wherein the modified loudspeaker positions include loudspeaker positions of the given set of loudspeakers and at least one additional virtual loudspeaker position, and downmixing the first preliminary decode matrix, wherein coefficients relating to the at least one additional virtual loudspeaker are removed and distributed to coefficients relating to the loudspeakers of the given set of loudspeakers. In one embodiment, a subsequent step of normalizing the decode matrix follows. The resulting decode matrix is suitable for rendering or decoding the soundfield signal to the given set of loudspeakers, wherein even sound from positions where no loudspeaker is present is reproduced with correct signal energy. This is due to the construction of the improved decode matrix. Preferably, the first preliminary decode matrix is energy-preserving.

Fig.4 a) shows a block diagram of an apparatus according to one embodiment. The apparatus 400 for decoding an encoded audio signal in soundfield format for L loudspeakers at known positions comprises an adder unit 410 for adding at least one position of at least one virtual loudspeaker to the positions of the L loudspeakers, a decode matrix generator unit 411 for generating a 3D decode matrix ***D'***, wherein the positions $\hat{\mathbf{\Omega}}_1$ ... $\hat{\mathbf{\Omega}}_L$ of the L loudspeakers and the at least one virtual position $\hat{\mathbf{\Omega}}'_{L+1}$ are used and the 3D decode matrix ***D'*** has coefficients for said determined and virtual loudspeaker positions, a matrix downmixing unit 412 for downmixing the 3D decode matrix ***D'***, wherein the coefficients for the virtual loudspeaker positions are weighted and distributed to coefficients relating to the determined loudspeaker positions, and wherein a downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$ is obtained having coefficients for the determined loudspeaker positions, and decoding unit 414 for decoding the encoded audio signal using the downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$, wherein a plurality of decoded loudspeaker signals is obtained.

In one embodiment, the apparatus further comprises a normalizing unit 413 for normalizing the downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$, wherein a normalized downscaled 3D decode matrix ***D*** is obtained, and the decoding unit 414 uses the normalized downscaled 3D decode matrix ***D***.

In one embodiment shown in Fig.4 b), the apparatus further comprises a first determining unit 4101 for determining positions ($\mathbf{\Omega}_L$) of the L loudspeakers and an order N of coefficients of the soundfield signal, a second determining unit 4102 for determining from the positions that the L loudspeakers are substantially in a 2D plane, and a virtual loudspeaker position generating unit 4103 for generating at least one virtual position ($\hat{\mathbf{\Omega}}'_{L+1}$) of a virtual loudspeaker.

In one embodiment, the apparatus further comprises a plurality of band pass filters 715b for separating the encoded audio signal into a plurality of frequency bands, wherein a plurality of separate 3D decode matrices ***D$_b$'*** are generated 711b, one for each frequency band, and each 3D decode matrix ***D$_b$'*** is downmixed 712b and optionally normalized separately, and wherein the decoding unit 714b decodes each frequency band separately. In this embodiment, the apparatus further comprises a plurality of adder units 716b, one for each loudspeaker. Each adder unit adds up the frequency bands that relate to the respective loudspeaker.

Each of the adder unit 410, decode matrix generator unit 411, matrix downmixing unit 412, normalization unit 413, decoding unit 414, first determining unit 4101, second determining unit 4102 and virtual loudspeaker position generating unit 4103 can be implemented by one or more processors, and each of these units may share the same processor with any other of these or other units.

Fig.7 shows an embodiment that uses separately optimized decode matrices for different frequency bands of the input signal. In this embodiment, the decoding method comprises a step of separating the encoded audio signal into a plurality of frequency bands using band pass filters. A plurality of separate 3D decode matrices $\boldsymbol{D_b}'$ are generated 711b, one for each frequency band, and each 3D decode matrix $\boldsymbol{D_b}'$ is downmixed 712b and optionally normalized separately. The decoding 714b of the encoded audio signal is performed for each frequency band separately. This has the advantage that frequency-dependent differences in human perception can be taken into consideration, and can lead to different decode matrices for different frequency bands. In one embodiment, only one or more (but not all) of the decode matrices are generated by adding virtual loudspeaker positions and then weighting and distributing their coefficients to coefficients for existing loudspeaker positions as described above. In another embodiment, each of the decode matrices is generated by adding virtual loudspeaker positions and then weighting and distributing their coefficients to coefficients for existing loudspeaker positions as described above. Finally, all the frequency bands that relate to the same loudspeaker are added up in one frequency band adder unit 716b per loudspeaker, in an operation reverse to the frequency band splitting.

Each of the adder unit 410, decode matrix generator unit 711b, matrix downmixing unit 712b, normalization unit 713b, decoding unit 714b, frequency band adder unit 716b and band pass filter unit 715b can be implemented by one or more processors, and each of these units may share the same processor with any other of these or other units.

One aspect of the present disclosure is to obtain a rendering matrix for a 2D setup with good energy preserving properties. In one embodiment, two virtual loudspeakers are added at the top and bottom (elevation angles +90° and -90° with the 2D loudspeakers placed approximately at an elevation of 0°). For this virtual 3D loudspeaker setup, a rendering matrix is designed that satisfies the energy preserving property. Finally the weighting factors from the rendering matrix for the virtual loudspeakers are mixed with constant gains to the real loudspeakers of the 2D setup.

In the following, Ambisonics (in particular HOA) rendering is described.

Ambisonics rendering is the process of computation of loudspeaker signals from an Ambisonics soundfield description. Sometimes it is also called Ambisonics decoding. A 3D Ambisonics soundfield representation of order N is considered, where the number of coefficients is

$$O_{3D} = (N+1)^2 \tag{1}$$

The coefficients for time sample t are represented by vector $\boldsymbol{b}(t) \in \mathbb{C}^{O_{3D} \times 1}$ with O_{3D} elements. With the rendering matrix $\boldsymbol{D} \in \mathbb{C}^{L \times O_{3D}}$ the loudspeaker signals for time sample t are computed by

$$\boldsymbol{w}(t) = \boldsymbol{D}\, \boldsymbol{b}(t) \tag{2}$$

with $\boldsymbol{D} \in \mathbb{C}^{L \times O_{3D}}$ and $\boldsymbol{w} \in \mathbb{R}^{L \times 1}$ and L being the number of loudspeakers.

The positions of the loudspeakers are defined by their inclination angles θ_l and azimuth angles ϕ_l which are combined into a vector $\widehat{\boldsymbol{\Omega}}_l = [\theta_l, \phi_l]^T$ for $l = 1, \dots, L$. Different loudspeaker distances from the listening position are compensated by using individual delays for the loudspeaker channels.

Signal energy in the HOA domain is given by

$$E = \boldsymbol{b}^H\, \boldsymbol{b} \tag{3}$$

where ^{H} denotes (conjugate complex) transposed. The corresponding energy of the loudspeaker signals is computed by

$$\hat{E} = \boldsymbol{w}^H\, \boldsymbol{w} = \boldsymbol{b}^H \boldsymbol{D}^H \boldsymbol{D}\, \boldsymbol{b}. \tag{4}$$

The ratio $\hat{E}/E$ for an energy preserving decode/rendering matrix should be constant in order to achieve energy-preserving decoding/rendering.

In principle, the following extension for improved 2D rendering is proposed: For the design of rendering matrices for 2D loudspeaker setups, one or more virtual loudspeakers are added. 2D setups are understood as those where the loudspeakers' elevation angles are within a defined small range, so that they are close to the horizontal plane. This can be expressed by

$$\left|\theta_l - \frac{\pi}{2}\right| \leq \theta_{thres2d};\ l = 1, \dots, L \tag{5}$$

The threshold value $\theta_{thres2d}$ is normally chosen to correspond to a value in the range of 5° to 10°, in one embodiment.

For the rendering design, a modified set of loudspeaker angles $\widehat{\boldsymbol{\Omega}}_l'$ is defined. The last (in this example two) loudspeaker positions are those of two virtual loudspeakers at the north and south poles (in vertical direction, ie. top and bottom) of the polar coordinate system:

$$\widehat{\boldsymbol{\Omega}}_l' = \widehat{\boldsymbol{\Omega}}_l;\ l = 1, \dots, L$$
$$\widehat{\boldsymbol{\Omega}}_{L+1}' = [0,0]^T \qquad (6)$$
$$\widehat{\boldsymbol{\Omega}}_{L+2}' = [\pi, 0]^T$$

Thus, the new number of loudspeaker used for the rendering design is $L' = L + 2$. From these modified loudspeaker positions, a rendering matrix $\boldsymbol{D}' \in \mathbb{C}^{(L+2)\times O_{3D}}$ is designed with an energy preserving approach. For example, the design method described in [1] can be used. Now the final rendering matrix for the original loudspeaker setup is derived from $\boldsymbol{D}'$. One idea is to mix the weighting factors for the virtual loudspeaker as defined in the matrix $\boldsymbol{D}'$ to the real loudspeakers. A fixed gain factor is used which is chosen as

$$g = \frac{1}{\sqrt{L}}. \qquad (7)$$

Coefficients of the intermediate matrix $\widetilde{\boldsymbol{D}} \in \mathbb{C}^{L\times O_{3D}}$ (also called downscaled 3D decode matrix herein) are defined by

$$\tilde{d}_{l,q} = d_{l,q}' + g \cdot d_{L+1,q}' + g \cdot d_{L+2,q}' \quad \text{for } l = 1, \dots, L \text{ and } q = 1, \dots, O_{3D} \qquad (8)$$

where $\tilde{d}_{l,q}$ is the matrix element of $\widetilde{\boldsymbol{D}}$ in the l-th row and the q-th column. In an optional final step, the intermediate matrix (downscaled 3D decode matrix) is normalized using the Frobenius norm:

$$\boldsymbol{D} = \frac{\widetilde{\boldsymbol{D}}}{\sqrt{\sum_{l=1}^{L} \sum_{q=1}^{O_{3D}} \left|\tilde{d}_{l,q}\right|^2}} \qquad (9)$$

Figs.5 and 6 show the energy distributions for a 5.0 surround loudspeaker setup. In both figures, the energy values are shown as greyscales and the circles indicate the loudspeaker positions. With the disclosed method, especially the attenuation at the top (and also bottom, not shown here) is clearly reduced.

Fig.5 shows energy distribution resulting from a conventional decode matrix. Small circles around the z=0 plane represent loudspeaker positions. As can be seen, an energy range of [-3.9, ..., 2.1] dB is covered, which results in energy differences of 6 dB. Further, signals from the top (and on the bottom, not visible) of the unit sphere are reproduced with very low energy, i.e. not audible, since no loudspeakers are available here.

Fig.6 shows energy distribution resulting from a decode matrix according to one or more embodiments, with the same amount of loudspeakers being at the same positions as in

Fig.5. At least the following advantages are provided: first, a smaller energy range of [-1.6, ..., 0.8] dB is covered, which results in smaller energy differences of only 2.4 dB. Second, signals from all directions of the unit sphere are reproduced with their correct energy, even if no loudspeakers are available here. Since these signals are reproduced through the available loudspeakers, their localization is not correct, but the signals are audible with correct loudness. In this example, signals from the top and on the bottom (not visible) become audible due to the decoding with the improved decode matrix.

In an embodiment, a method for decoding an encoded audio signal in Ambisonics format for L loudspeakers at known positions comprises steps of adding at least one position of at least one virtual loudspeaker to the positions of the L loudspeakers, generating a 3D decode matrix ***D'***, wherein the positions $\hat{\mathbf{\Omega}}_{1,\ldots,}\hat{\mathbf{\Omega}}_{L}$ of the L loudspeakers and the at least one virtual position $\hat{\mathbf{\Omega}}'_{L+1}$ are used and the 3D decode matrix ***D'*** has coefficients for said determined and virtual loudspeaker positions, downmixing the 3D decode matrix ***D'***, wherein the coefficients for the virtual loudspeaker positions are weighted and distributed to coefficients relating to the determined loudspeaker positions, and wherein a downscaled 3D decode matrix $\widetilde{\boldsymbol{D}}$ is obtained having coefficients for the determined loudspeaker positions, and decoding the encoded audio signal using the downscaled 3D decode matrix $\widetilde{\boldsymbol{D}}$, wherein a plurality of decoded loudspeaker signals is obtained.

In another embodiment, an apparatus for decoding an encoded audio signal in Ambisonics format for L loudspeakers at known positions comprises an adder unit 410 for adding at least one position of at least one virtual loudspeaker to the positions of the L loudspeakers, a decode matrix generator unit 411 for generating a 3D decode matrix ***D'***, wherein the positions $\hat{\mathbf{\Omega}}_1 \ldots \hat{\mathbf{\Omega}}_L$ of the L loudspeakers and the at least one virtual position $\hat{\mathbf{\Omega}}'_{L+1}$ are used and the 3D decode matrix ***D'*** has coefficients for said determined and virtual loudspeaker positions, a matrix downmixing unit 412 for downmixing the 3D decode matrix ***D'***, wherein the coefficients for the virtual loudspeaker positions are weighted and distributed to coefficients relating to the determined loudspeaker positions, and wherein a downscaled 3D decode matrix $\widetilde{\boldsymbol{D}}$ is obtained having coefficients for the determined loudspeaker positions, and a decoding unit 414 for decoding the encoded audio signal using the downscaled 3D decode matrix $\widetilde{\boldsymbol{D}}$, wherein a plurality of decoded loudspeaker signals is obtained.

In yet another embodiment, an apparatus for decoding an encoded audio signal in Ambisonics format for L loudspeakers at known positions comprises at least one processor and at least one memory, the memory having stored instructions that when executed on the processor implement an adder unit 410 for adding at least one position of at least one virtual loudspeaker to the positions of the L loudspeakers, a decode matrix generator unit 411 for generating a 3D decode matrix ***D'***, wherein the positions $\hat{\mathbf{\Omega}}_1 \ldots \hat{\mathbf{\Omega}}_L$ of the L loudspeakers and the at least one virtual position $\hat{\mathbf{\Omega}}'_{L+1}$ are used and the 3D decode matrix ***D'*** has coefficients for said determined and virtual loudspeaker positions, a matrix downmixing unit 412 for downmixing the 3D decode matrix ***D'***, wherein the coefficients for the virtual loudspeaker positions are weighted and distributed to coefficients relating to the determined loudspeaker positions, and wherein a downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$ is obtained having coefficients for the determined loudspeaker positions, and a decoding unit 414 for decoding the encoded audio signal using the downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$, wherein a plurality of decoded loudspeaker signals is obtained.

In yet another embodiment, a computer readable storage medium has stored thereon executable instructions to cause a computer to perform a method for decoding an encoded audio signal in Ambisonics format for L loudspeakers at known positions, wherein the method comprises steps of adding at least one position of at least one virtual loudspeaker to the positions of the L loudspeakers, generating a 3D decode matrix ***D'***, wherein the positions $\hat{\mathbf{\Omega}}_{1, \ldots,} \hat{\mathbf{\Omega}}_L$ of the L loudspeakers and the at least one virtual position $\hat{\mathbf{\Omega}}'_{L+1}$ are used and the 3D decode matrix ***D'*** has coefficients for said determined and virtual loudspeaker positions, downmixing the 3D decode matrix ***D'***, wherein the coefficients for the virtual loudspeaker positions are weighted and distributed to coefficients relating to the determined loudspeaker positions, and wherein a downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$ is obtained having coefficients for the determined loudspeaker positions, and decoding the encoded audio signal using the downscaled 3D decode matrix $\tilde{\boldsymbol{D}}$, wherein a plurality of decoded loudspeaker signals is obtained. Further embodiments of computer readable storage media can include any features described above, in particular features disclosed in the dependent claims referring back to claim 1.

It will be understood that the present invention has been described purely by way of example, and modifications of detail can be made without departing from the scope of the invention. For example, although described only with respect to HOA, the invention can also be applied for other soundfield audio formats.
Each feature disclosed in the description and (where appropriate) the claims and drawings may be provided independently or in any appropriate combination. Features may, where appropriate be implemented in hardware, software, or a combination of the

two. Reference numerals appearing in the claims are by way of illustration only and shall have no limiting effect on the scope of the claims.

The following references have been cited above.

[1] International Patent Publication No. WO2014/012945A1 (PD120032)
[2] F. Zotter and M. Frank, “All-Round Ambisonic Panning and Decoding”, J. Audio Eng. Soc., 2012, Vol. 60, pp. 807-820

<u>Claims</u>

1. A method for decoding an encoded audio signal in Ambisonics format for L loudspeakers at known positions, comprising steps of
   - adding (10) at least one position of at least one virtual loudspeaker to the positions of the L loudspeakers;
   - generating (11) a 3D decode matrix (***D'***), wherein the positions ($\hat{\boldsymbol{\Omega}}_1, \ldots, \hat{\boldsymbol{\Omega}}_L$) of the L loudspeakers and the at least one virtual position ($\hat{\boldsymbol{\Omega}}'_{L+1}$) are used and the 3D decode matrix (***D'***) has coefficients for said determined and virtual loudspeaker positions;
   - downmixing (12) the 3D decode matrix (***D'***), wherein the coefficients for the virtual loudspeaker positions are weighted and distributed to coefficients relating to the determined loudspeaker positions, and wherein a downscaled 3D decode matrix ($\tilde{\boldsymbol{D}}$) is obtained having coefficients for the determined loudspeaker positions; and
   - decoding (14) the encoded audio signal (i14) using the downscaled 3D decode matrix ($\tilde{\boldsymbol{D}}$), wherein a plurality of decoded loudspeaker signals (q14) is obtained.

2. The method according to claim 1, wherein the coefficients for the virtual loudspeaker positions are weighted with a weighting factor $g = \frac{1}{\sqrt{L}}$, wherein L is the number of loudspeakers.

3. The method according to claim 1 or 2, wherein the at least one virtual position ($\hat{\boldsymbol{\Omega}}'_{L+1}$) of a virtual loudspeaker is one of $\hat{\boldsymbol{\Omega}}'_{L+1} = [0,0]^T$ and $\hat{\boldsymbol{\Omega}}'_{L+1} = [\pi, 0]^T$.

4. The method according to any of claims 1-3, further comprising a step of normalizing (13) the downscaled 3D decode matrix ($\tilde{\boldsymbol{D}}$) using a Frobenius norm, wherein a normalized downscaled 3D decode matrix (***D***) is obtained, and the step of decoding (14) the encoded audio signal uses the normalized downscaled 3D decode matrix (***D***).

5. The method according to claim 4, wherein the normalizing is performed according to

$$\boldsymbol{D} = \frac{\tilde{\boldsymbol{D}}}{\sqrt{\sum_{l=1}^{L} \sum_{q=1}^{\mathrm{O}_{3\mathrm{D}}} \left|\tilde{d}_{l,q}\right|^2}} .$$

6. The method according to any of the claims 1-5, further comprising steps of

- determining (101) positions ($\hat{\mathbf{\Omega}}_1$ ... $\hat{\mathbf{\Omega}}_L$) of the L loudspeakers and an order N of coefficients of the soundfield signal;
- determining (102) from the positions that the L loudspeakers are substantially in a 2D plane; and
- generating (103) at least one virtual position ($\hat{\mathbf{\Omega}}'_{L+1}$) of a virtual loudspeaker.

7. The method according to any of claims 1-6, further comprising a step of separating the encoded audio signal into a plurality of frequency bands using band pass filters, wherein a plurality of separate 3D decode matrices ($\boldsymbol{D_b}'$) are generated (711b), one for each frequency band, and each 3D decode matrix ($\boldsymbol{D_b}'$) is downmixed (712b) and optionally normalized separately (713b), and wherein the step of decoding (714b) the encoded audio signal (i14) is performed for each frequency band separately.

8. The method according to any of claims 1-7, wherein the known L loudspeaker positions are substantially within one 2D plane, with elevations of not more than 10°.

9. An apparatus for decoding an encoded audio signal in Ambisonics format for L loudspeakers at known positions, comprising
   - adder unit (410) for adding at least one position of at least one virtual loudspeaker to the positions of the L loudspeakers;
   - decode matrix generator unit (411) for generating a 3D decode matrix ($\boldsymbol{D}'$), wherein the positions ($\hat{\mathbf{\Omega}}_1$ ... $\hat{\mathbf{\Omega}}_L$) of the L loudspeakers and the at least one virtual position ($\hat{\mathbf{\Omega}}'_{L+1}$) are used and the 3D decode matrix ($\boldsymbol{D}'$) has coefficients for said determined and virtual loudspeaker positions;
   - matrix downmixing unit (412) for downmixing the 3D decode matrix ($\boldsymbol{D}'$), wherein the coefficients for the virtual loudspeaker positions are weighted and distributed to coefficients relating to the determined loudspeaker positions, and wherein a downscaled 3D decode matrix ($\widetilde{\boldsymbol{D}}$) is obtained having coefficients for the determined loudspeaker positions; and
   - decoding unit (414) for decoding the encoded audio signal (i14) using the downscaled 3D decode matrix ($\widetilde{\boldsymbol{D}}$), wherein a plurality of decoded loudspeaker signals (q14) is obtained.

10. The apparatus according to claim 9, further comprising a normalizing unit (413) for normalizing the downscaled 3D decode matrix ($\widetilde{\boldsymbol{D}}$) using a Frobenius norm, wherein

a normalized downscaled 3D decode matrix (***D***) is obtained, and the decoding unit (414) uses the normalized downscaled 3D decode matrix (***D***).

11. The apparatus according to claim 9 or 10, further comprising
    - first determining unit (101) for determining positions ($\hat{\mathbf{\Omega}}_1 \ldots \hat{\mathbf{\Omega}}_L$) of the L loudspeakers and an order N of coefficients of the soundfield signal;
    - second determining unit (102) for determining from the positions that the L loudspeakers are substantially in a 2D plane; and
    - virtual loudspeaker position generating unit (103) for generating at least one virtual position ($\hat{\mathbf{\Omega}}'_{L+1}$) of a virtual loudspeaker.

12. The apparatus according to one of the claims 9-11, further comprising a plurality of band pass filters (715b) for separating the encoded audio signal into a plurality of frequency bands, wherein a plurality of separate 3D decode matrices ($\boldsymbol{D_b}'$) are generated (711b), one for each frequency band, and each 3D decode matrix ($\boldsymbol{D_b}'$) is downmixed (712b) and optionally normalized separately, and wherein the decoding unit (714b) decodes each frequency band separately.

13. A computer readable storage medium having stored thereon executable instructions to cause a computer to perform a method for decoding an encoded audio signal in Ambisonics format for L loudspeakers at known positions, the method comprising steps of
    - adding (10) at least one position of at least one virtual loudspeaker to the positions of the L loudspeakers;
    - generating (11) a 3D decode matrix ($\boldsymbol{D}'$), wherein the positions ($\hat{\mathbf{\Omega}}_1, \ldots, \hat{\mathbf{\Omega}}_L$) of the L loudspeakers and the at least one virtual position ($\hat{\mathbf{\Omega}}'_{L+1}$) are used and the 3D decode matrix ($\boldsymbol{D}'$) has coefficients for said determined and virtual loudspeaker positions;
    - downmixing (12) the 3D decode matrix ($\boldsymbol{D}'$), wherein the coefficients for the virtual loudspeaker positions are weighted and distributed to coefficients relating to the determined loudspeaker positions, and wherein a downscaled 3D decode matrix ($\widetilde{\boldsymbol{D}}$) is obtained having coefficients for the determined loudspeaker positions; and
    - decoding (14) the encoded audio signal (i14) using the downscaled 3D decode matrix ($\widetilde{\boldsymbol{D}}$), wherein a plurality of decoded loudspeaker signals (q14) is obtained.

14. The computer readable storage medium according to claim 13, wherein the coefficients for the virtual loudspeaker positions are weighted with a weighting factor $g = \frac{1}{\sqrt{L}}$, wherein L is the number of loudspeakers.

15. The computer readable storage medium according to claim 13 or 14, wherein the at least one virtual position ($\widehat{\mathbf{\Omega}}'_{L+1}$) of a virtual loudspeaker is one of $\widehat{\mathbf{\Omega}}'_{L+1} = [0,0]^T$ and $\widehat{\mathbf{\Omega}}'_{L+1} = [\pi, 0]^T$.

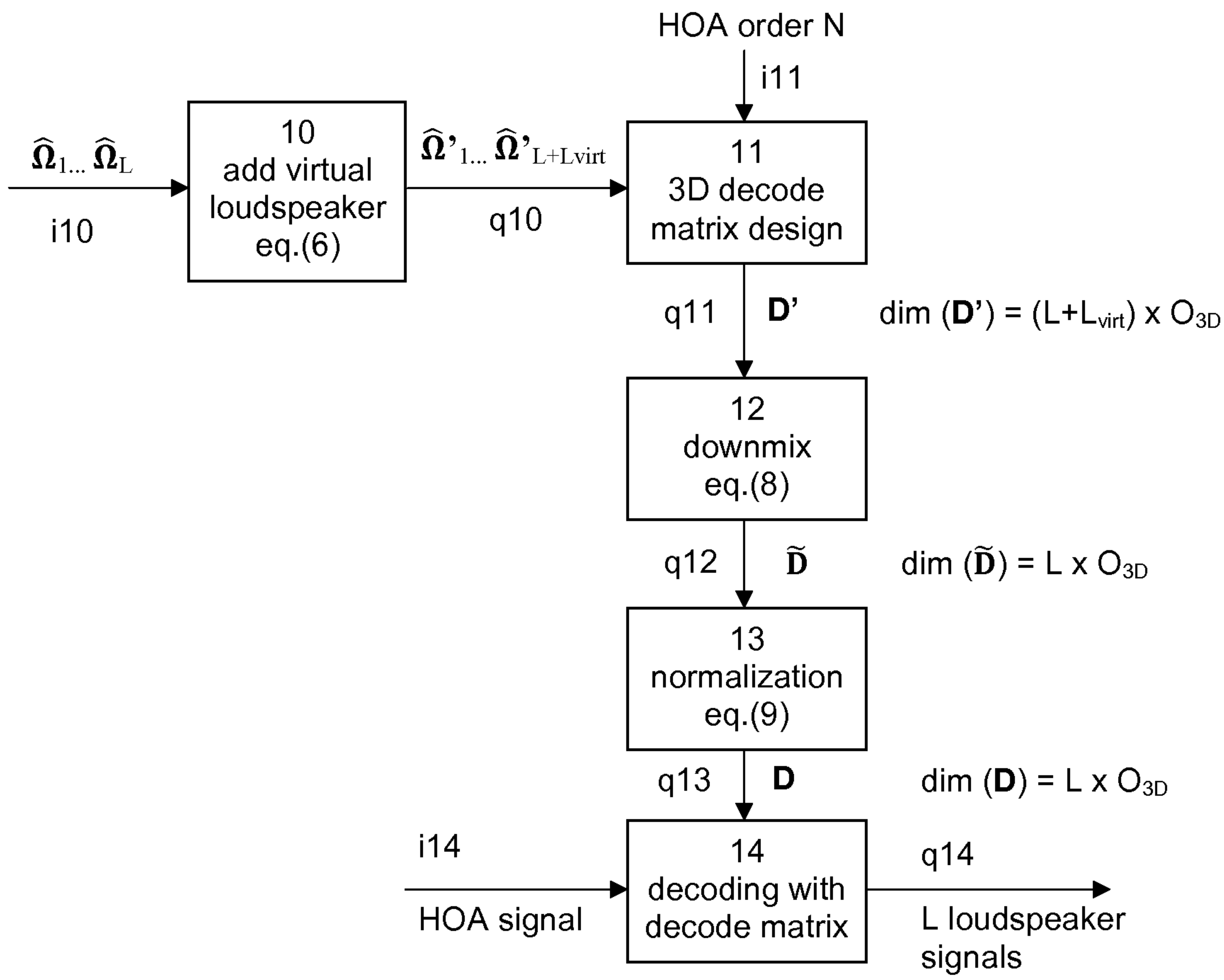


Fig.1

$$\boldsymbol{D}' = \begin{bmatrix} d'_{1,1} & d'_{1,2} & \dots & d'_{1,O3D} \\ \dots & \dots & \dots & \dots \\ d'_{L,1} & d'_{L,2} & \dots & d'_{L,O3D} \\ d'_{L+1,1} & d'_{L+1,2} & \dots & d'_{L+1,O3D} \\ d'_{L+2,1} & d'_{L+2,2} & \dots & d'_{L+2,O3D} \end{bmatrix} \rightarrow \widetilde{\boldsymbol{D}} = \begin{bmatrix} \tilde{d}_{1,1} & \tilde{d}_{1,2} & \dots & \tilde{d}_{1,O3D} \\ \dots & \dots & \dots & \dots \\ \tilde{d}_{L,1} & \tilde{d}_{L,2} & \dots & \tilde{d}_{L,O3D} \end{bmatrix}$$

$$\boldsymbol{D}' = \begin{bmatrix} d'_{1,1} & d'_{1,2} & \dots & d'_{1,O3D} \\ \dots & \dots & \dots & \dots \\ d'_{L,1} & d'_{L,2} & \dots & d'_{L,O3D} \\ d'_{L+1,1} & d'_{L+1,2} & \dots & d'_{L+1,O3D} \\ d'_{L+2,1} & d'_{L+2,2} & \dots & d'_{L+2,O3D} \end{bmatrix} \rightarrow \widetilde{\boldsymbol{D}} = \begin{bmatrix} \tilde{d}_{1,1} & \tilde{d}_{1,2} & \dots & \tilde{d}_{1,O3D} \\ \dots & \dots & \dots & \dots \\ \tilde{d}_{L,1} & \tilde{d}_{L,2} & \dots & \tilde{d}_{L,O3D} \end{bmatrix}$$

Fig.2

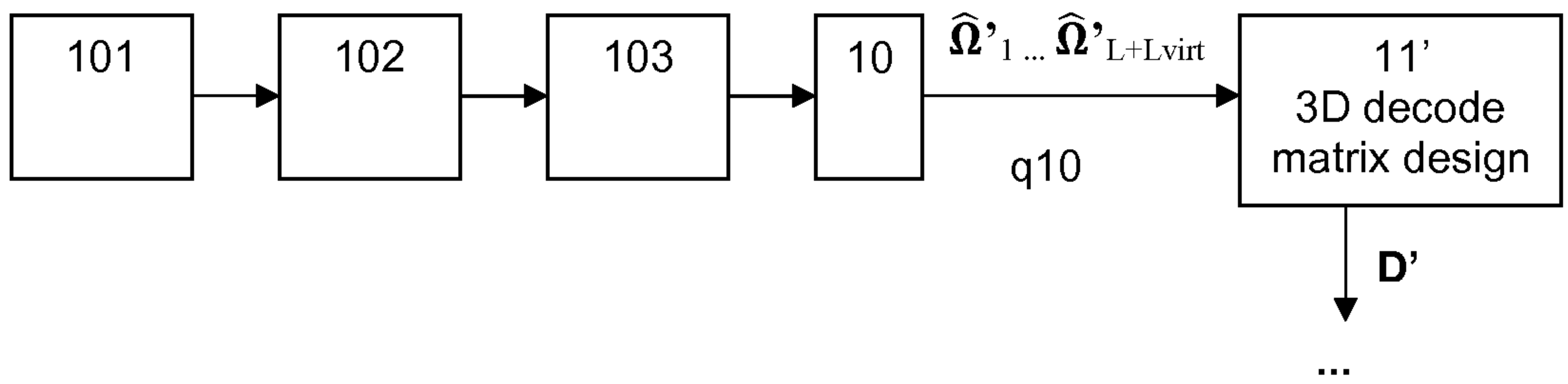
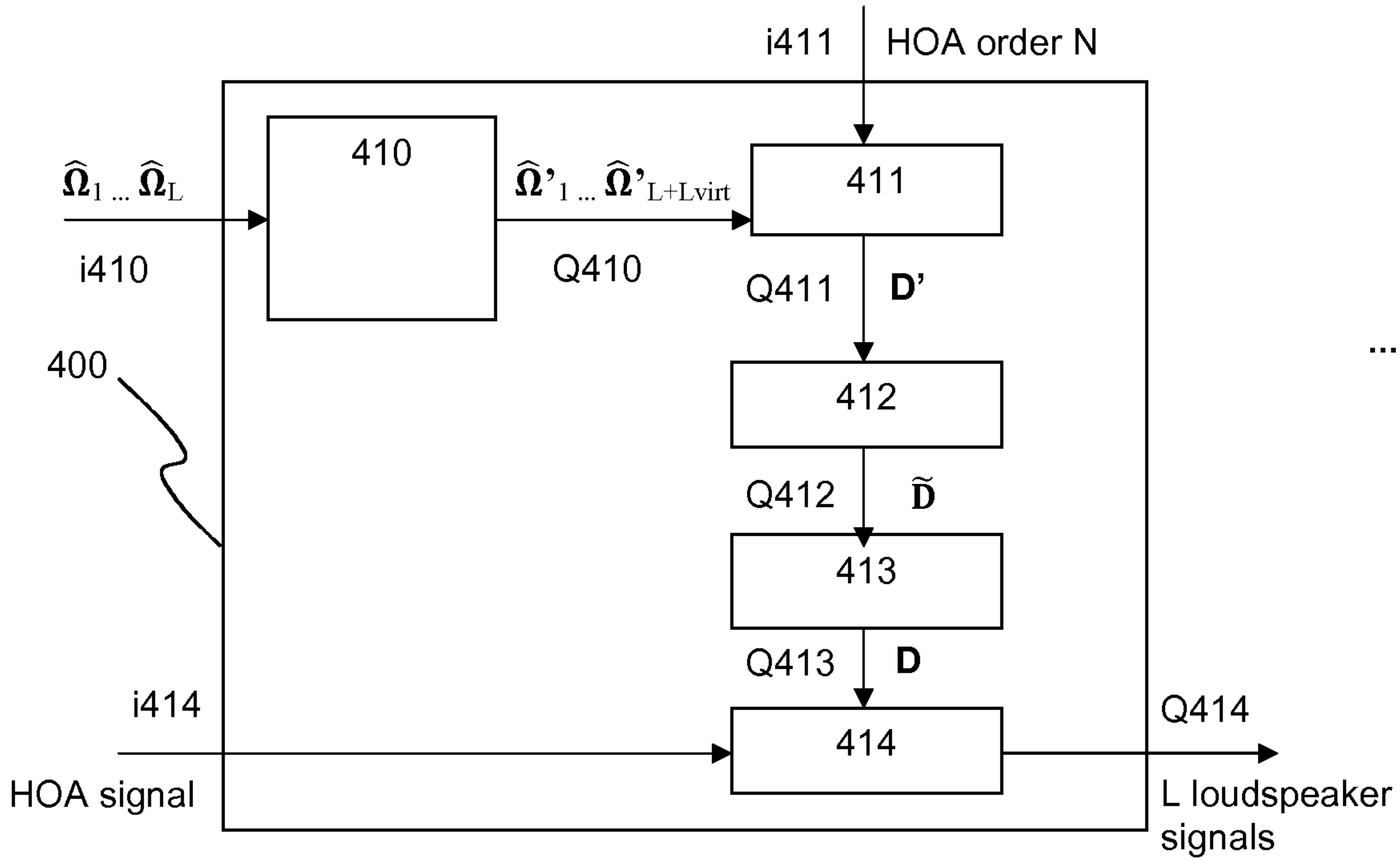
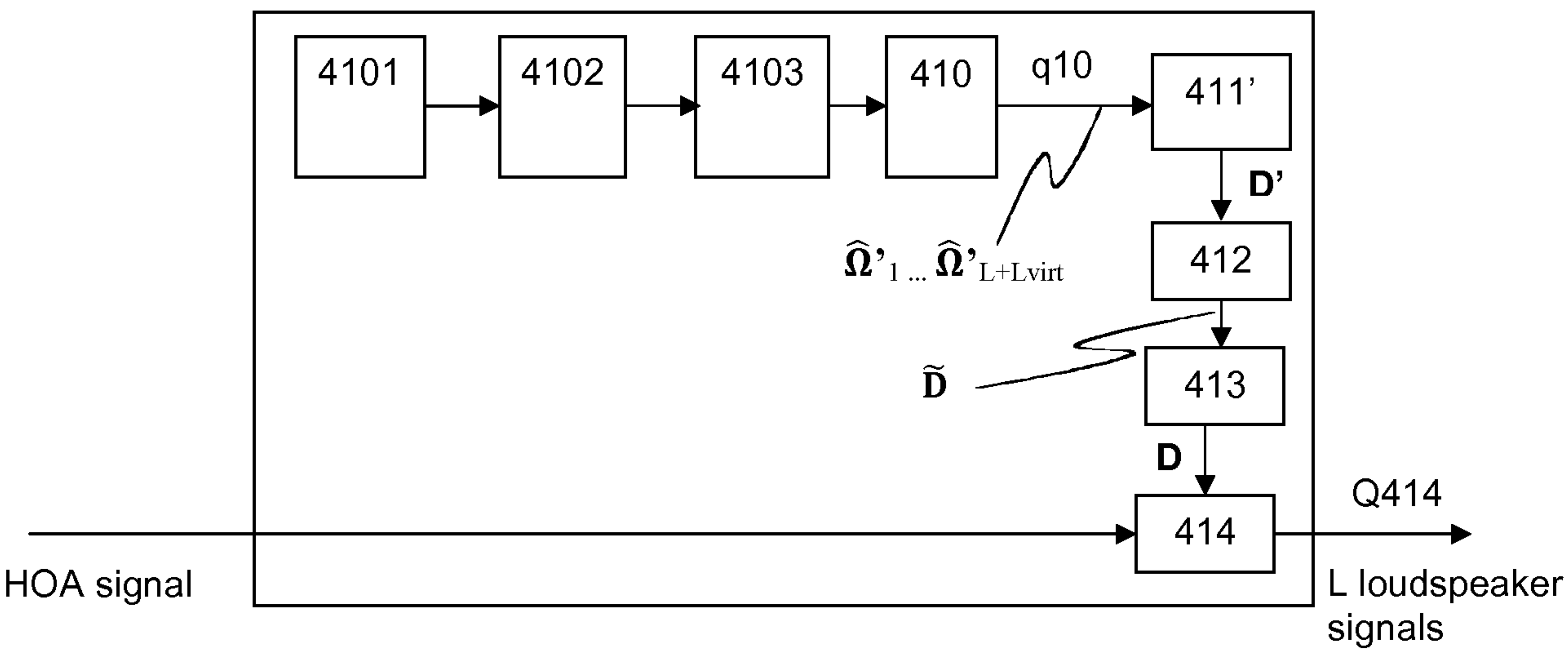

101
102
103
10
$\hat{\mathbf{\Omega}}'_1 \dots \hat{\mathbf{\Omega}}'_{L+Lvirt}$
q10
11'
3D decode
matrix design
D'
...

Fig.3


i411
HOA order N
$\hat{\mathbf{\Omega}}_1 \dots \hat{\mathbf{\Omega}}_L$
i410
410
$\hat{\mathbf{\Omega}}'_1 \dots \hat{\mathbf{\Omega}}'_{L+Lvirt}$
Q410
411
Q411
D'
400
412
Q412
$\tilde{\mathbf{D}}$
413
Q413
D
i414
414
Q414
HOA signal
L loudspeaker signals
...

a)


4101
4102
4103
410
q10
411'
D'
$\hat{\mathbf{\Omega}}'_1 \dots \hat{\mathbf{\Omega}}'_{L+Lvirt}$
412
$\tilde{\mathbf{D}}$
413
D
414
Q414
HOA signal
L loudspeaker signals

b)

Fig.4

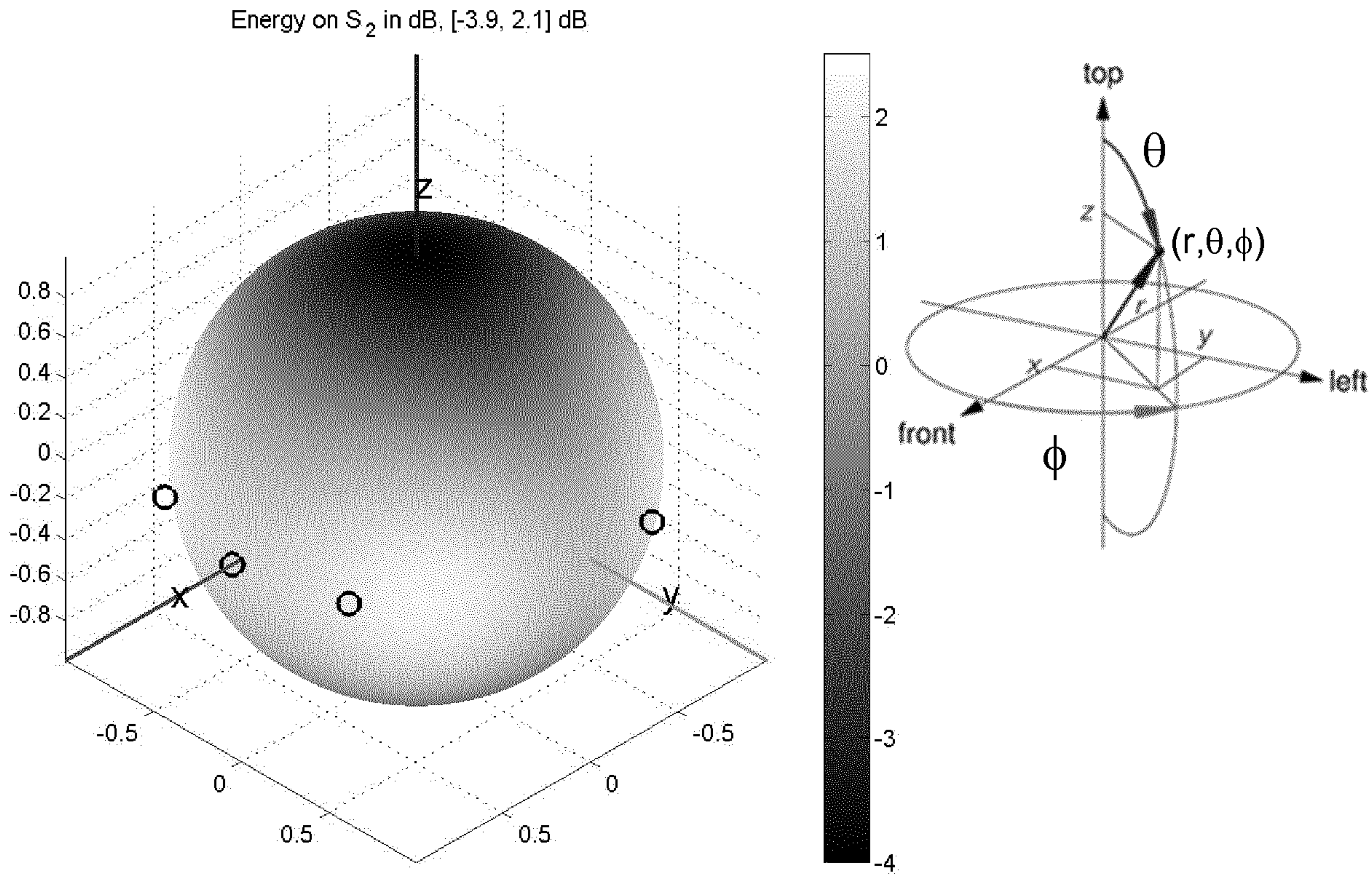

Energy on S_2 in dB, [-3.9, 2.1] dB
z
x
y
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.5
0
0.5
-0.5
0
0.5
2
1
0
-1
-2
-3
-4
top
θ
z
(r,θ,ϕ)
r
y
x
left
front
ϕ

Fig.5

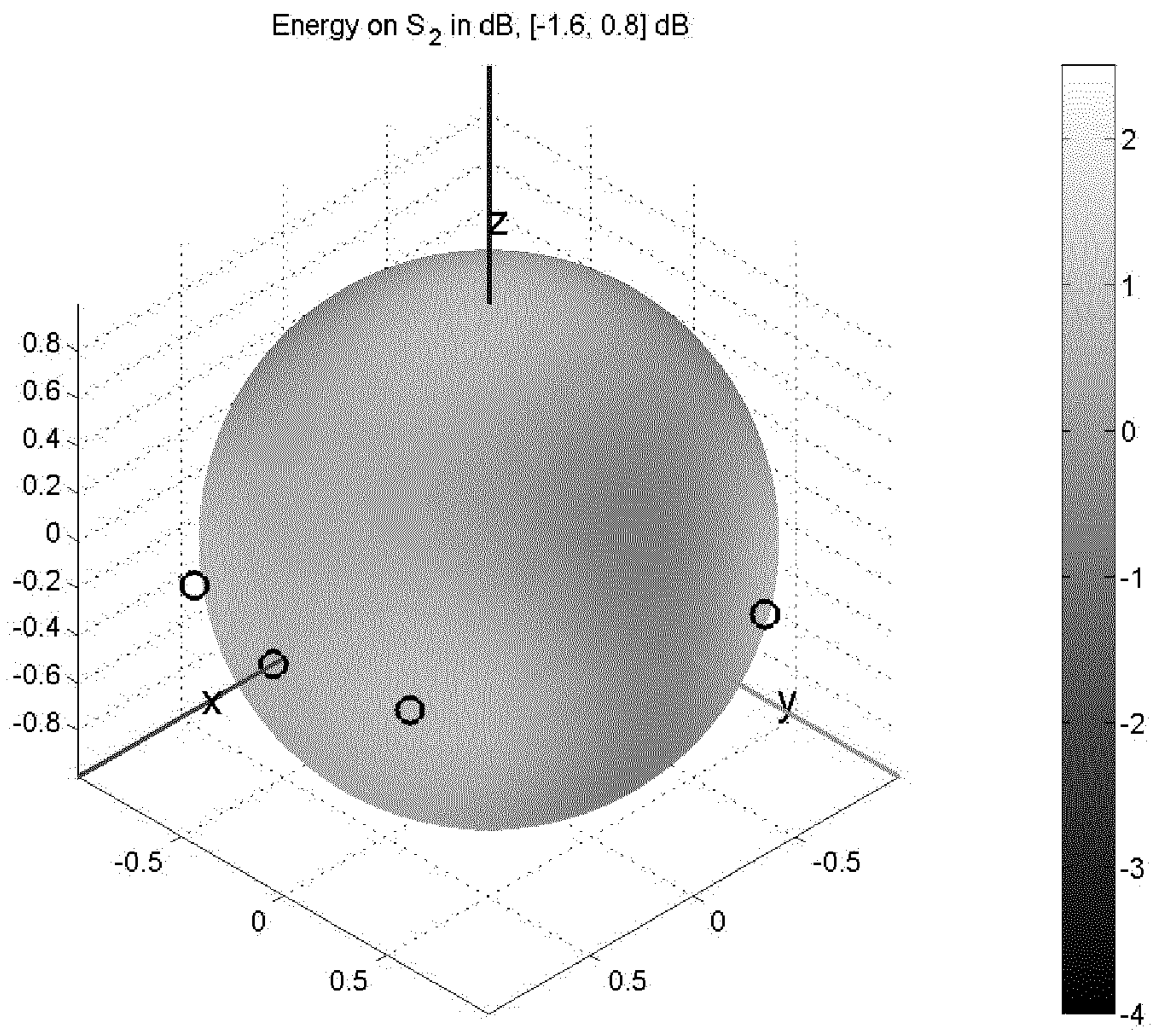

Energy on S_2 in dB, [-1.6, 0.8] dB
z
x
y
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.5
0
0.5
-0.5
0
0.5
2
1
0
-1
-2
-3
-4

Fig.6

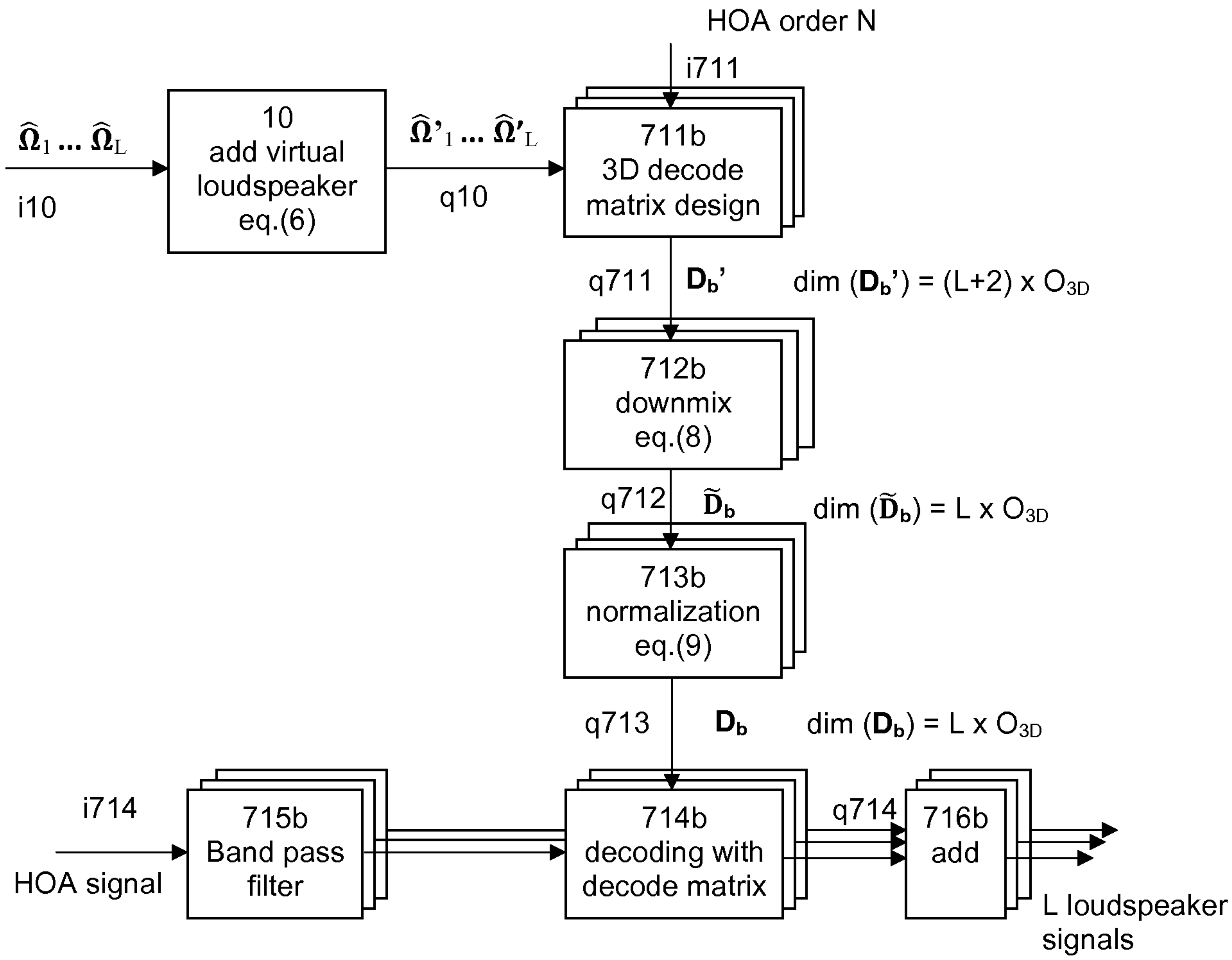

HOA order N
i711
Ω̂1 ... Ω̂L
i10
10
add virtual
loudspeaker
eq.(6)
Ω̂'1 ... Ω̂'L
q10
711b
3D decode
matrix design
q711
Db'
dim (Db') = (L+2) x O3D
712b
downmix
eq.(8)
q712
D̃b
dim (D̃b) = L x O3D
713b
normalization
eq.(9)
q713
Db
dim (Db) = L x O3D
i714
HOA signal
715b
Band pass
filter
714b
decoding with
decode matrix
q714
716b
add
L loudspeaker
signals

Fig.7

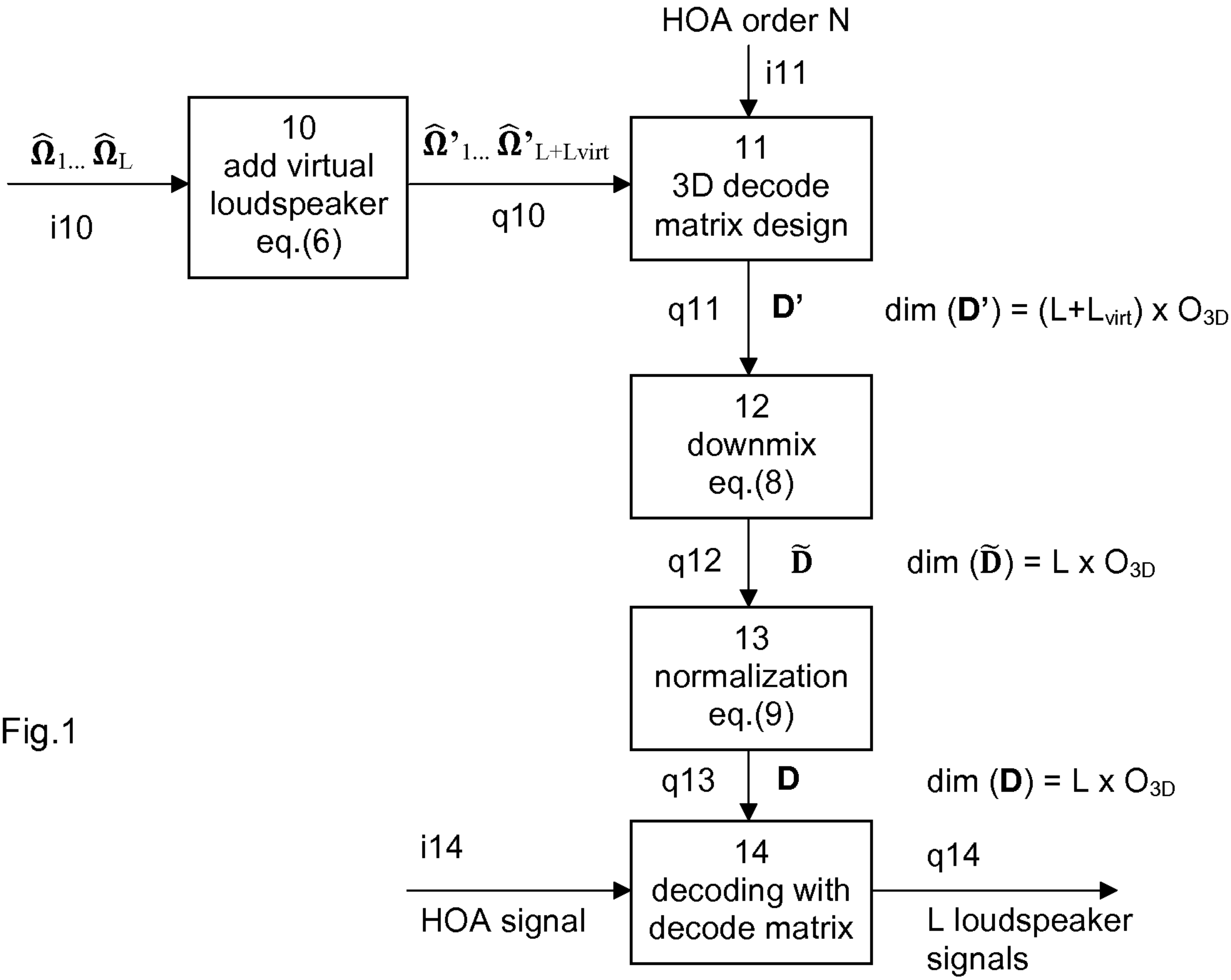


Fig.1

$$(\hat{\mathbf{\Omega}}_1 \ldots \hat{\mathbf{\Omega}}_L) \quad \text{(I)}$$

$$(\hat{\mathbf{\Omega}}'_{L+1}) \quad \text{(II)}$$

$$(\tilde{\boldsymbol{D}}) \quad \text{(III)}$$