SERIES T: TERMINALS FOR TELEMATIC SERVICES

Still-image compression – JPEG 2000

Information technology – JPEG 2000 image coding system: Extensions for three-dimensional data

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For further details, please refer to the list of ITU-T Recommendations.
Information technology – JPEG 2000 image coding system:
Extensions for three-dimensional data

Summary


Corrigendum 1 (05/2011, integrated in this new edition) corrects a number of minor mistakes that were present in various formulae of Annex B. It also provides a more formal and unambiguous description on the mandatory use of the CAP marker segment in the codestream, in order to enhance interoperability with the other parts of the JPEG 2000 standard. Furthermore, it introduces a new annex on how quantization should be handled for JP3D images.

History

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FOREWORD

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The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

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Introduction

Rec. ITU-T T.809 | ISO/IEC 15444-10 was prepared jointly by ITU-T Study Group 16, Multimedia coding, systems and applications, and Joint Technical Committee ISO/IEC JTC 1, Information Technology, Subcommittee SC 29, Coding of audio, picture, multimedia and hypermedia information.

ISO/IEC 15444 consists of the following parts, under the general title Information technology – JPEG 2000 image coding system:

– Part 1: Core coding system
– Part 2: Extensions
– Part 3: Motion JPEG 2000
– Part 4: Conformance testing
– Part 5: Reference software
– Part 6: Compound image file format
– Part 8: Secure JPEG 2000
– Part 9: Interactivity tools, APIs and protocols
– Part 10: Extensions for three-dimensional data
– Part 11: Wireless
– Part 12: ISO base media file format
– Part 13: Entry Level JPEG 2000 Encoder
ISO/IEC 15444-10:2011 (E)

INTERNATIONAL STANDARD
RECOMMENDATION ITU-T

Information technology – JPEG 2000 image coding system:
Extensions for three-dimensional data

1 Scope

2 Normative references
The following Recommendations and International Standards contain provisions which, through reference in this text, constitute provisions of this Recommendation | International Standard. At the time of publication, the editions indicated were valid. All Recommendations and Standards are subject to revision, and parties to agreements based on this Recommendation | International Standard are encouraged to investigate the possibility of applying the most recent edition of the Recommendations and Standards listed below. Members of IEC and ISO maintain registers of currently valid International Standards. The Telecommunication Standardization Bureau of the ITU maintains a list of currently valid ITU-T Recommendations.

3 Terms and definitions
For the purposes of this Recommendation | International Standard, the following definitions apply:

3.1 **3D bit-block**: A three-dimensional array of bits. In this Recommendation | International Standard, a 3D bit-block refers to all the bits of the same magnitude in all coefficients or samples. This could refer to a 3D bit-block in a component, tile-component, 3D code-block, region of interest, or other.

3.2 **3D code-block**: A rectangular three-dimensional grouping of coefficients from the same sub-band of a tile-component.

3.3 **3D code-block scan**: The order in which the coefficients within a 3D code-block are visited during a coding pass. The 3D code-block is processed in stripes, each consisting of four rows (or all remaining rows if less than four) and spanning the width of the 3D code-block. Each stripe is processed column by column from top to bottom and from left to right. The complete 3D code-block is consequently scanned slice by slice. Within a slice, Rec. ITU-T T.800 | ISO/IEC 15444-1 is followed.

3.4 **component (update of Rec. ITU-T T.801 | ISO/IEC 15444-2)**: Compressed data from the codestream representing a single set of two- or three-dimensional data.

3.5 **conforming reader (update of Rec. ITU-T T.800 | ISO/IEC 15444-1)**: An application that reads and interprets a JP3D file correctly.

3.6 **decomposition level (update of Rec. ITU-T T.801 | ISO/IEC 15444-2)**: A collection of sub-bands where each coefficient has the same spatial impact or span with respect to the original samples. These include the [H][L][X][H][L][X][H][L][X] sub-band (e.g., LLL, LXL, XXH, ..., exclusive XXX) split out of the three-dimensional decomposition sublevels.
3.7 **[H|L|X][H|L|X][H|L|X] sub-band**: H refers to high-pass filtering and L to low-pass filtering, while X refers to no filtering. The filter specified first refers to the horizontal filtering, the second to the vertical filtering and the third to the axial filtering (i.e., respectively along X-, Y- and Z-axes). The filter ordering for this sub-band should always be respected. The reconstruction will follow the inverse filtering order.

NOTE – The XXX sub-band does not exist (as defined in 3.6).

3.8 **image (update of Rec. ITU-T T.800 | ISO/IEC 15444-1)**: The set of all components, which can have either two- or three-spatial dimensions.

3.9 **image area offset (update of Rec. ITU-T T.800 | ISO/IEC 15444-1)**: The number of reference grid points down, to the right (and to an increased axial position) of the reference grid origin.


3.11 **raster order (update of Rec. ITU-T T.800 | ISO/IEC 15444-1)**: A particular sequential order of data of any type within an array. The raster order starts with the top left data point of the first slice and moves to the data point immediately to the right, and so on to the end of the row. After the end of the row is reached, the next data point in the sequence is the left-most data point immediately below the current row. This order is continued to the end of the slice. Thereafter the next slice is processed in case of a three-dimensional array. This order is continued to the end of the array.

3.12 **resolution (update of Rec. ITU-T T.801 | ISO/IEC 15444-2)**: The spatial relation of samples to a physical space. In this Recommendation | International Standard, the decomposition levels of the wavelet transform create resolutions that differ by powers of two in the horizontal, the vertical, or – in the three-dimensional case – the axial direction, or any possible combination of directions. The last (highest) decomposition level includes an \([L|X][L|X][L|X]\) sub-band (note that XXX is non-existing), which is considered to be a lower resolution. Therefore, there is one more resolution level than decomposition levels.

3.13 **resolution level (update of Rec. ITU-T T.801 | ISO/IEC 15444-1)**: Equivalent to decomposition level with the exception that the \([L|X][L|X][L|X]\) sub-band is also a separate resolution level.

3.14 **sample (update of Rec. ITU-T T.800 | ISO/IEC 15444-1)**: One element in the two-dimensional or three-dimensional array that comprises a component.

3.15 **slice**: A slice is a two-dimensional pixel subset of a volumetric entity, a volumetric code-block or a volumetric image. A slice is positioned perpendicular to the axial or z-axis.

3.16 **spatial coordinates**: Spatial coordinates are indicated by \(x\), \(y\) and \(z\). Generally, the term axial will be used to address the \(Z\) dimension.

3.17 **sub-band (update of Rec. ITU-T T.800 | ISO/IEC 15444-1)**: A group of transform coefficients resulting from the same sequence of low-pass and high-pass filtering operations.

3.18 **sub-band order**: Within one resolution level, sub-bands are processed and signalled as defined in Rec. ITU-T T.800 | ISO/IEC 15444-1 and Rec. ITU-T T.801 | ISO/IEC 15444-2 for two-dimensional filtering, following a Morton scanning order [1]. The specification is extended to the three-dimensional case by deploying consequently a three-dimensional Morton scanning order.

3.19 **tile (update of Rec. ITU-T T.800 | ISO/IEC 15444-1)**: A cuboidal array of points on the reference grid, registered with an offset from the reference grid origin and defined by a width (\(x\) dimension), a height (\(y\) dimension) and a depth (\(z\) dimension). The tiles that overlap are used to define tile-components.

4 **Abbreviations**

For the purposes of this Recommendation | International Standard, the abbreviations defined in clause 4 of Rec. ITU-T T.800 | ISO/IEC 15444-1, and clause 4 of Rec. ITU-T T.801 | ISO/IEC 15444-2 also apply to this Recommendation | International Standard.

5 **Symbols (and abbreviated terms)**

For the purposes of this Recommendation | International Standard, the symbols defined in clause 4 of Rec. ITU-T T.800 | ISO/IEC 15444-1, and clause 5 of Rec. ITU-T T.801 | ISO/IEC 15444-2 also apply to this Recommendation | International Standard.
6 General description

This Recommendation | International Standard defines a set of lossless (bit-preserving) and lossy compression methods for coding continuous-tone, bi-level, grey-scale, colour digital volumetric images, or multi-component volumetric images. This set of methods (see Annex A) extends the elements in the core coding system described in Rec. ITU-T T.800 | ISO/IEC 15444-1 and Rec. ITU-T T.801 | ISO/IEC 15444-2. Extensions which pertain to encoding and decoding are defined as procedures which may be used in combination with the encoding and decoding processes described in Rec. ITU-T T.800 | ISO/IEC 15444-1 and Rec. ITU-T T.801 | ISO/IEC 15444-2. Each encoding or decoding extension shall be used only in combination with particular coding processes and only in accordance with the requirements set forth herein. This Recommendation | International Standard also defines extensions to the compressed data format, i.e., interchange format and the abbreviated formats.

In particular, for Rec. ITU-T T.801 | ISO/IEC 15444-2, the following extensions are supported by this Recommendation | International Standard:

1) variable DC offset;
2) arbitrary wavelet transform kernels;
3) multi-component transformations;
4) non-linear transformations;
5) region-of-interest.
Annex A

Codestream syntax, extension

(This annex forms an integral part of this Recommendation | International Standard.)

A.1 Extended capabilities


In every marker segment, the first two bytes after the marker shall be an unsigned value that denotes the length in bytes of the marker segment parameters (including the two bytes of this length parameter but not the two bytes of the marker itself).

When a marker segment that is not specified in this Recommendation | International Standard or in Rec. ITU-T T.800 | ISO/IEC 15444-1 and Rec. ITU-T T.801 | ISO/IEC 15444-2 is encountered in a codestream, the decoder shall use the length parameter to discard the marker segment. Table A.1 shows the marker segment usage specified for this Recommendation | International Standard.

![Table A.1 – List of markers and marker segments](image-url)
Table A.1 – List of markers and marker segments

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Code</th>
<th>Main header</th>
<th>Tile-part header</th>
<th>Rec. ITU-T T.80x</th>
<th>ISO/IEC 15444-x Heritage/Extended</th>
</tr>
</thead>
</table>

**Pointer marker segments**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Code</th>
<th>Main header</th>
<th>Tile-part header</th>
<th>Rec. ITU-T T.80x</th>
<th>ISO/IEC 15444-x Heritage/Extended</th>
</tr>
</thead>
</table>

**In bit stream markers and marker segments**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Code</th>
<th>Main header</th>
<th>Tile-part header</th>
<th>Rec. ITU-T T.80x</th>
<th>ISO/IEC 15444-x Heritage/Extended</th>
</tr>
</thead>
</table>

**Informational marker segments**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Code</th>
<th>Main header</th>
<th>Tile-part header</th>
<th>Rec. ITU-T T.80x</th>
<th>ISO/IEC 15444-x Heritage/Extended</th>
</tr>
</thead>
</table>

* Required means the marker or marker segment shall be in this header, optional means it may be used.


#### A.2.1 Additional dimension image and tile size (NSI)

**Function:** Provides information about the uncompressed image such as the depth of the reference grid, the depth of the tiles, and the separation of component samples with respect to the reference grid.

**Usage:** Main header. There shall be one and only one in the main header.
Length: Variable depending on the number of components.

<table>
<thead>
<tr>
<th>NSI</th>
<th>Lnsi</th>
<th>Ndim</th>
<th>Zsiz</th>
<th>ZOsiz</th>
<th>ZTsiz</th>
<th>ZTOsiz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure A.1 – Additional dimension image and tile size syntax (extended)

NSI: Marker code. Table A.2 shows the size and parameter values of the symbol and parameters for additional dimension image and tile size marker segment.

Lnsi: Length of marker segment in bytes (not including the marker). The value of this parameter is determined by the following equation:

\[ L_{nsi} = 19 + C_{siz} \]  

\[ \text{(A-1)} \]

Ndim: Defines the dimensionality of the dataset (disregarding the component dimension). This value is set to 3 by default.

Zsiz: Depth of the reference grid.

ZOsiz: Depth offset from the origin of the reference grid to the front left upper corner of the image volume.

ZTsiz: Depth of one reference tile with respect to the reference grid.

ZTOsiz: Vertical offset from the origin of the reference grid to the front left upper corner of the first tile.

ZRsiz\(^i\): Depth separation of a sample of the \(i\)th component with respect to the reference grid. There is one occurrence of this parameter for each component, in order.

Table A.2 – Additional dimension image and tile size parameter values (extended)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size (bits)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSI</td>
<td>16</td>
<td>0xFF54</td>
</tr>
<tr>
<td>Lnsi</td>
<td>16</td>
<td>20-16403</td>
</tr>
<tr>
<td>Ndim</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Zsiz</td>
<td>32</td>
<td>1-(2^{32} – 1)</td>
</tr>
<tr>
<td>ZOsiz</td>
<td>32</td>
<td>0-(2^{32} – 1)</td>
</tr>
<tr>
<td>ZTsiz</td>
<td>32</td>
<td>1-(2^{32} – 1)</td>
</tr>
<tr>
<td>ZTOsiz</td>
<td>32</td>
<td>1-(2^{32} – 2)</td>
</tr>
<tr>
<td>ZRsiz(^i)</td>
<td>8</td>
<td>1-255</td>
</tr>
</tbody>
</table>

A.2.2 Coding style default (COD), Rec. ITU-T T.800 | ISO/IEC 15444-1 extended

Function: Describes the coding style, number of decomposition levels and layering that is the default used for compressing all components of an image (if in the main header) or a tile (if in the tile-part header). The parameter values can be overridden for an individual component by a COC marker segment in either the main or tile-part header.

Usage: Main and first tile-part header of a given tile. There shall be one and only one in the main header. Additionally, there may be at most one for each tile. If there are multiple tile-parts in a tile, and this marker segment is present, it shall be found only in the first tile-part (\(TPsot = 0\)).

When used in the main header, the COD marker segment parameter values are used for all tile-components that do not have a corresponding COC marker segment in either the main or tile-part header. When used in the tile-part header, it overrides the main header COD and COCs and is used for all components in that tile without a corresponding COD marker segment in the tile-part. Thus, the order of precedence is the following:

Tile-part COC > Tile-part COD > Main COC > Main COD

where the "greater than" sign, >, means that the greater overrides the lesser marker segment.

Length: Variable depending on the value of Scod (see Lcod parameter).
Figure A.2 – Coding style default syntax

COD: Marker code. Table A.3 shows the size and values of the symbol and parameters for coding style default marker segment.

Lcod: Length of marker segment in bytes (not including the marker). The value of this parameter is determined by the following equation:

\[
L_{\text{loc}} = \begin{cases} 
17 & \text{maximum_precincts} \\
17 + 2 \cdot \text{number_of_resolution_levels} & \text{user_defined_precincts}
\end{cases}
\]  

where maximum_precincts and user_defined_precincts are indicated in the Scod parameter and number_of_resolution_levels is calculated by use of the number of decomposition level parameters for each of the three dimensions, X, Y and Z, as indicated in the SPcod parameter. The actual equation for calculating the number of resolution levels is given in B.5.

Scod: Coding style for all components. Table A.4 shows the value for the Scod parameter.

SGcod: Parameters for coding style designated in Scod. The parameters are independent of components and are designated, in order from top to bottom, in Table A.5. The coding style parameters within the SGcod field appear in the sequence shown in Figure A.3.

SPcod: Parameters for coding style designated in Scod. The parameters relate to all components and are designated, in order from top to bottom, in Table A.6. The coding style parameters within the SPcod field appear in the sequence shown in Figure A.3.

Table A.3 – Coding style default parameters values, extended

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size (bits)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>16</td>
<td>0xFF52</td>
</tr>
<tr>
<td>Lcod</td>
<td>16</td>
<td>17-83</td>
</tr>
<tr>
<td>Scod</td>
<td>8</td>
<td>Table A.4</td>
</tr>
<tr>
<td>SGcod</td>
<td>32</td>
<td>Table A.5</td>
</tr>
<tr>
<td>SPcod</td>
<td>variable</td>
<td>Table A.6</td>
</tr>
</tbody>
</table>

Figure A.3 – Coding style parameter diagram of the SGcod and SPcod parameters
### Table A.4 – Coding style parameter values for the Scod parameter

<table>
<thead>
<tr>
<th>Values (bits)</th>
<th>MSB</th>
<th>LSB</th>
<th>Coding style</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxxx xxx0</td>
<td></td>
<td></td>
<td>Entropy coder, precincts with ( PPx = 15, PPy = 15 ) and ( PPz = 15 )</td>
</tr>
<tr>
<td>xxxx xxx1</td>
<td></td>
<td></td>
<td>Entropy coder with custom precincts defined below</td>
</tr>
<tr>
<td>xxxx xx0x</td>
<td></td>
<td></td>
<td>No SOP marker segments used</td>
</tr>
<tr>
<td>xxxx xx1x</td>
<td></td>
<td></td>
<td>SOP marker segments may be used</td>
</tr>
<tr>
<td>xxxx x0xx</td>
<td></td>
<td></td>
<td>No EPH marker used</td>
</tr>
<tr>
<td>xxxx x1xx</td>
<td></td>
<td></td>
<td>EPH marker shall be used</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>All other values reserved</td>
</tr>
</tbody>
</table>

### Table A.5 – Coding style parameter values for the SGcod parameter

<table>
<thead>
<tr>
<th>Parameters (in order)</th>
<th>Size (bits)</th>
<th>Values</th>
<th>Meaning of SGcod values</th>
</tr>
</thead>
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<td>Progression order</td>
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<td>Rec. ITU-T T.800</td>
<td>Progression order</td>
</tr>
<tr>
<td>Number of layers</td>
<td>16</td>
<td>1-65535</td>
<td>Number of layers</td>
</tr>
<tr>
<td>Multiple component transform</td>
<td>8</td>
<td>Rec. ITU-T T.801</td>
<td>Multiple component transform usage</td>
</tr>
</tbody>
</table>

### Table A.6 – Coding style parameter values of the SPcod and SPcoc parameters, extended

<table>
<thead>
<tr>
<th>Parameters (in order)</th>
<th>Size (bits)</th>
<th>Values</th>
<th>Meaning of SPcod values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of decomposition levels along X-axis</td>
<td>8</td>
<td>0-32</td>
<td>Number of decomposition levels along X-axis, ( N_{X,0}), zero implies no transformation</td>
</tr>
<tr>
<td>Number of decomposition levels along Y-axis</td>
<td>8</td>
<td>0-32</td>
<td>Number of decomposition levels along Y-axis, ( N_{Y,0}), zero implies no transformation</td>
</tr>
<tr>
<td>Number of decomposition levels along Z-axis</td>
<td>8</td>
<td>0-32</td>
<td>Number of decomposition levels along Z-axis, ( N_{Z,0}), zero implies no transformation</td>
</tr>
<tr>
<td>3D code-block width</td>
<td>8</td>
<td>Table A.7</td>
<td>Code-block width exponent offset value, ( x_{cb} )</td>
</tr>
<tr>
<td>3D code-block height</td>
<td>8</td>
<td>Table A.7</td>
<td>Code-block height exponent offset value, ( y_{cb} )</td>
</tr>
<tr>
<td>3D code-block depth</td>
<td>8</td>
<td>Table A.7</td>
<td>Code-block depth exponent offset value, ( z_{cb} )</td>
</tr>
<tr>
<td>3D code-block style</td>
<td>8</td>
<td>Table A.8</td>
<td>Style of the 3D code-block coding passes</td>
</tr>
<tr>
<td>Transformation kernel along X-axis</td>
<td>8</td>
<td>Rec. ITU-T T.801</td>
<td>Wavelet transformation used along X-axis</td>
</tr>
<tr>
<td>Transformation kernel along Y-axis</td>
<td>8</td>
<td>Rec. ITU-T T.801</td>
<td>Wavelet transformation used along Y-axis</td>
</tr>
<tr>
<td>Transformation kernel along Z-axis</td>
<td>8</td>
<td>Rec. ITU-T T.801</td>
<td>Wavelet transformation used along Z-axis</td>
</tr>
<tr>
<td>Precinct size</td>
<td>variable</td>
<td>Table A.9</td>
<td>If ( Scod ) or ( Scoc ) = xxxx xxx0, this parameter is not present; otherwise, this indicates precinct width, height and depth. The first parameter (16 bits) corresponds to the ( N_{L,LL} ) sub-band. Each successive parameter corresponds to each successive resolution level in order.</td>
</tr>
</tbody>
</table>
### Table A.7 – Width, height or depth exponent of the 3D code-blocks for the SPcod and SPcoc parameters

<table>
<thead>
<tr>
<th>Values (bits) MSB LSB</th>
<th>3D code-block width, height and depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxxxxxxx 0000 – xxxxxxxx 1011</td>
<td>3D code-block width, height and depth exponent values $x_{cb} = \text{value}$, $y_{cb} = \text{value}$ or $z_{cb} = \text{value}$.</td>
</tr>
<tr>
<td></td>
<td>NOTE – This redefines Rec. ITU-T T.800</td>
</tr>
</tbody>
</table>

All other values reserved

### Table A.8 – 3D code-block style for the SPcod and SPcoc parameters, extended

<table>
<thead>
<tr>
<th>Values (bits) MSB LSB</th>
<th>3D code-block style</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxxxxxxx xxx0</td>
<td>No selective arithmetic coding bypass</td>
</tr>
<tr>
<td>xxxxxxxx xxx1</td>
<td>Selective arithmetic coding bypass</td>
</tr>
<tr>
<td>xxxxxxxx xx0x</td>
<td>No reset of context probabilities on coding pass boundaries</td>
</tr>
<tr>
<td>xxxxxxxx xx1x</td>
<td>Reset context probabilities on coding pass boundaries</td>
</tr>
<tr>
<td>xxxxxxxx x0xx</td>
<td>No termination on each coding pass</td>
</tr>
<tr>
<td>xxxxxxxx x1xx</td>
<td>Termination on each coding pass</td>
</tr>
<tr>
<td>xxxxxxxx 0xxx</td>
<td>No causal contexts</td>
</tr>
<tr>
<td>xxxxxxxx 1xxx</td>
<td>Causal contexts</td>
</tr>
<tr>
<td>xxxxxxxx 0xxx</td>
<td>No predictable termination</td>
</tr>
<tr>
<td>xxxxxxxx 1xxx</td>
<td>Predictable termination</td>
</tr>
<tr>
<td>xxxxxxxx 0xxx</td>
<td>No segmentation symbols are used</td>
</tr>
<tr>
<td>xxxxxxxx 1xxx</td>
<td>Segmentation symbols are used</td>
</tr>
</tbody>
</table>

All other values reserved

### Table A.9 – Precinct width, height and depth for the SPcod and SPcoc parameters, extended

<table>
<thead>
<tr>
<th>Values (bits) MSB LSB</th>
<th>Precinct size</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxxxxxxx xxxxx 0000 – xxxxxxxx xxxxx 1111</td>
<td>4 LSBs are the precinct width exponent $PP_x = \text{value}$. This value may only equal zero at the resolution level corresponding to the $N_{j_{LLL}}$ band.</td>
</tr>
<tr>
<td>xxxxxxxx xxxxx 0000 – xxxxxxxx xxxxx 1111 xxxxx</td>
<td>Next 4 bits are the precinct height exponent $PP_y = \text{value}$. This value may only equal zero at the resolution level corresponding to the $N_{j_{LLL}}$ band.</td>
</tr>
<tr>
<td>xxxxxxxx xxxxx 0000 – xxxxxxxx xxxxx 1111 xxxxx xxxxx</td>
<td>Next 4 bits are the precinct depth exponent $PP_z = \text{value}$. This value may only equal zero at the resolution level corresponding to the $N_{j_{LLL}}$ band.</td>
</tr>
</tbody>
</table>

All other values reserved

### A.2.3 Coding style component (COC), Rec. ITU-T T.800 | ISO/IEC 15444-1 extended

**Function:** Describes the coding style and number of decomposition levels used for compressing a particular component.

**Usage:** Main and first tile-part header of a given tile. The usage is optional in both the main and tile-part headers. No more than one per any given component may be present in either the main or tile-part headers. If there are multiple tile-parts in a tile, and this marker segment is present, it shall be found only in the first tile-part ($TP_{set} = 0$). When used in the main header, it overrides the main COD marker segment for the specific component. When used in the tile-part header, it overrides the main header COD, main COC and tile COD for the specific component. Thus, the order of precedence is the following:

Tile-part COC > Tile-part COD > Main COC > Main COD

where the “greater than” sign, $>$, means that the greater overrides the lesser marker segment.
Length: Variable depending on the value of Scoc (see Lcoc parameter).

![Figure A.4 – Coding style component syntax](image)

- **COC:** Marker code. Table A.10 shows the size and values of the symbol and parameters for the coding style component marker segment.
- **Lcoc:** Length of marker segment in bytes (not including the marker). The value of this parameter is determined by the following equation:

  \[
  L_{coc} = \begin{cases} 
  14 & \text{maximum_precincts AND } Csiz < 257 \\
  15 & \text{maximum_precincts AND } Csiz \geq 257 \\
  14 + 2 \cdot \text{number_of_resolution_levels} & \text{user_defined_precincts AND } Csiz < 257 \\
  15 + 2 \cdot \text{number_of_resolution_levels} & \text{user_defined_precincts AND } Csiz \geq 257 
  \end{cases}
  \]  

  \[ \text{(A-3)} \]

- **Ccoc:** The index of the component to which this marker segment relates. The components are indexed 0, 1, 2, etc.
- **Scoc:** Coding style for this component. Table A.11 shows the values for each Scoc parameter.
- **SPcoc:** Parameters for coding style designated in Scoc. The coding style parameters within the SPcoc field appear in the order sequence shown in Figure A.5.

![Figure A.5 – Coding style parameter diagram of the SPcoc parameter](image)

**Table A.10 – Coding style component parameter values, extended**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size (bits)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>COC</td>
<td>16</td>
<td>0xFF53</td>
</tr>
<tr>
<td>Lcoc</td>
<td>16</td>
<td>4-102</td>
</tr>
<tr>
<td>Ccoc</td>
<td>8</td>
<td>0-255; if Csiz &lt; 257</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0-16383; if Csiz \geq 257</td>
</tr>
<tr>
<td>Scoc</td>
<td>8</td>
<td>Table A.11</td>
</tr>
<tr>
<td>SPcoc(^{i})</td>
<td>variable</td>
<td>Table A.6</td>
</tr>
</tbody>
</table>
Table A.11 – Coding style parameter values for the Scoc parameter, extended

<table>
<thead>
<tr>
<th>Values (bits) MSB</th>
<th>LSB</th>
<th>Coding style</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxxx xxxx0</td>
<td></td>
<td>Entropy coder with maximum precinct values PPx = PPy = PPz = 15</td>
</tr>
<tr>
<td>xxxx xxxx1</td>
<td></td>
<td>Entropy coder with precinct values defined in SPcoc</td>
</tr>
<tr>
<td>All other values reserved</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A.2.4 Region-of-interest (RGN), Rec. ITU-T T.801 | ISO/IEC 15444-2 extended

Function: Signals the presence of a region-of-interest (ROI) in the codestream.

Usage: Main and first tile-part header of a given tile. If there is RGN marker segment in the main header with a Srgn = 0, there shall not be any RGN marker segment anywhere in the codestream with a non-zero Srgn value for the component given by the corresponding Crgn value. Likewise, if there is RGN marker segment in the main header with a non-zero Srgn value, there shall not be any RGN marker segment anywhere in the codestream with a Srgn = 0 for the component given by the corresponding Crgn value.

When used in both the main header and the first tile-part header, the RGN in the first tile-part header overrides the main RGN for that tile. Also, an RGN specifying a single component (Crgn ≠ 65 535) overrides on specifying all components (Crgn = 65 535). Thus the order of precedence is the following:

Tile-part RGN (Crgn ≠ 65 535) > Tile-part RGN (Crgn = 65 535) > Main RGN (Crgn ≠ 65 535) > Main RGN (Crgn = 65 535)

where the "greater than" sign, >, means that the greater overrides the lesser marker segment.

Length: Variable.

Figure A.6 – Region-of-interest syntax

RGN: Marker code. Table A.12 shows the size and values of the symbol and parameters for the region of interest marker segment.

Lrgn: Length of the marker segment in bytes (not including the marker).

Crgn: The index of the component to which this marker segment relates. The components are indexed 0, 1, 2, etc.

Srgn: ROI style for the current ROI. Table A.16 of Rec. ITU-T T.801 | ISO/IEC 15444-2 shows the value for the Srgn parameter.

SPrgn: Parameter for ROI style designated in Srgn. SPrgn is only signalled for Srgn = 1 or Srgn = 2.

Table A.12 – Region-of-interest parameter values, extended

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size (bits)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGN</td>
<td>16</td>
<td>0xFF5E</td>
</tr>
<tr>
<td>Lrgn</td>
<td>16</td>
<td>5-30</td>
</tr>
<tr>
<td>Crgn</td>
<td>16</td>
<td>Rec. ITU-T T.801</td>
</tr>
<tr>
<td>Srgn</td>
<td>8</td>
<td>Rec. ITU-T T.801</td>
</tr>
<tr>
<td>SPrgn</td>
<td>variable</td>
<td>Table A.13</td>
</tr>
</tbody>
</table>
Table A.13 – Region of interest values from $SP_{r_{gn}}$ parameter ($S_{rgn} = 1$ or $S_{rgn} = 2$), extended

<table>
<thead>
<tr>
<th>Parameters (in order)</th>
<th>Size (bits)</th>
<th>Values</th>
<th>Meaning of $SP_{r_{gn}}$ values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary shift</td>
<td>8</td>
<td>0-255</td>
<td>Binary shifting of coefficients in the region of interest above the background.</td>
</tr>
<tr>
<td>XArgn (left)</td>
<td>32</td>
<td>0-$(2^{32} – 1)$</td>
<td>Horizontal reference grid point from the origin of the first point. (In the case of the ellipse, $S_{rgn} = 2$, this value shall not exceed the width of the image.)</td>
</tr>
<tr>
<td>YArgn (top)</td>
<td>32</td>
<td>0-$(2^{32} – 1)$</td>
<td>Vertical reference grid point from the origin of the first point. (In the case of the ellipse, $S_{rgn} = 2$, this value shall not exceed the height of the image.)</td>
</tr>
<tr>
<td>ZArgn (front)</td>
<td>32</td>
<td>0-$(2^{32} – 1)$</td>
<td>Axial reference grid point from the origin of the first point. (In the case of the ellipse, $S_{rgn} = 2$, this value shall not exceed the depth of the image.)</td>
</tr>
<tr>
<td>XBrng (right)</td>
<td>32</td>
<td>0-$(2^{32} – 1)$</td>
<td>Horizontal reference grid point from the origin of the second point.</td>
</tr>
<tr>
<td>YBrng (bottom)</td>
<td>32</td>
<td>0-$(2^{32} – 1)$</td>
<td>Vertical reference grid point from the origin of the second point.</td>
</tr>
<tr>
<td>ZBrng (back)</td>
<td>32</td>
<td>0-$(2^{32} – 1)$</td>
<td>Axial reference grid point from the origin of the second point.</td>
</tr>
</tbody>
</table>

A.2.5 Quantization component default (QCD), Rec. ITU-T T.800 | ISO/IEC 15444-1 extended

**Function:** Describes the quantization default used for compressing all components not defined by a QCC marker segment. The parameter values can be overridden for an individual component by a QCC marker segment in either the main or tile-part header.

**Usage:** Main and first tile-part header of a given tile. There shall be one and only one in the main header. There may be at most one for all tile-part headers of a tile. If there are multiple tile-parts for a tile, and this marker segment is present, it shall be found only in the first tile-part ($TP_{sot} = 0$).

When used in the tile-part header, it overrides the main QCD and the main QCC for the specific component. Thus, the order of precedence is the following:

Tile-part QCC > Tile-part QCD > Main QCC > Main QCD

where the "greater than" sign, >, means that the greater overrides the lesser marker segment.

**Length:** Variable depending on the number of quantized elements.

![Figure A.7 – Quantization default style](image)

**QCD:** Marker code. Table A.14 shows the size and values of the symbol and parameters for the quantization default marker segment.

**Lqcd:** Length of the marker segment in bytes (not including the marker). The value of this parameter is determined by the following equation:

\[
Lqcd = \begin{cases} 
4 + \text{number of sub-bands} & \text{no quantization} \\
5 & \text{scalar quantization derived} \\
5 + 2 \cdot \text{number of sub-bands} & \text{scalar quantization expounded}
\end{cases} \tag{A-4}
\]

where \text{number of sub-bands} (depending on number of decomposition levels along X, Y and Z axis) is defined in the COD and COC marker segments, and \text{no quantization}, \text{scalar quantization derived}, or \text{scalar quantization expounded} is signalled in the $Sq_{cd}$ parameter.

**NOTE** – The Lqcd can be used to determine how many quantization step sizes are present in the marker segment. However, there is not necessarily a correspondence with the number of sub-bands present because the sub-bands can be truncated with no requirement to correct this marker segment.
**Sqcd:** Quantization style for all components.

**SPqcd**: Quantization step size value for the ith sub-band in the defined order (see Annex B). The number of parameters is the same as the number of sub-bands in the tile-component with the greatest number of decomposition levels, N_L.

### Table A.14 – Quantization default parameter values, extended

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size (bits)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD</td>
<td>16</td>
<td>0xFF5C</td>
</tr>
<tr>
<td>Lqcd</td>
<td>16</td>
<td>4-441</td>
</tr>
<tr>
<td>Sqcd</td>
<td>8</td>
<td>Rec. ITU-T T.800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Table A.28</td>
</tr>
<tr>
<td>SPqcd</td>
<td>variable</td>
<td>Rec. ITU-T T.800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Table A.28</td>
</tr>
</tbody>
</table>

### A.2.6 Quantization component (QCC), Rec. ITU-T T.800 | ISO/IEC 15444-1 extended

**Function:** Describes the quantization used for compressing a particular component.

**Usage:** Main and first tile-part header of a given tile. Usage is optional in both the main and tile-part headers. No more than one per any given component may be present in either the main or tile-part headers. If there are multiple tile-parts in a tile, and this marker segment is present, it shall be found only in the first tile-part (TPsof = 0).

Optional in both the main and tile-part headers. When used in the main header, it overrides the main QCD marker segment for the specific component. When used in the tile-part header, it overrides the main QCD, main QCC, and tile QCD for the specific component. Thus, the order of precedence is the following:

Tile-part QCC > Tile-part QCD > Main QCC > Main QCD

where the "greater than" sign, >, means that the greater overrides the lesser marker segment.

**Length:** Variable depending on the number of quantized elements.

![Figure A.8 – Quantization component syntax](image)

**QCC:** Marker code. Table A.15 shows the size and values of the symbol and parameters for the quantization component marker segment.

**QCC:**

### Lqcc:
Length of the marker segment in bytes (not including the marker). The value of this parameter is determined by the following equation:

\[
Lqcc = \begin{cases} 
5 + \text{number_of_subbands} & \text{no_quantization AND } Csize < 257 \\
6 & \text{scalar_quantization_derived AND } Csize < 257 \\
6 + 2 \cdot \text{number_of_subbands} & \text{scalar_quantization_expounded AND } Csize < 257 \\
6 + \text{number_of_subbands} & \text{no_quantization AND } Csize \geq 257 \\
7 & \text{scalar_quantization_derived AND } Csize \geq 257 \\
7 + 2 \cdot \text{number_of_subbands} & \text{scalar_quantization_expounded AND } Csize \geq 257 
\end{cases}
\]  

(A-5)

**NOTE –** The Lqcc can be used to determine how many step sizes are present in the marker segment. However, there is not necessarily a correspondence with the number of sub-bands present because the sub-bands can be truncated with no requirement to correct this marker segment.
Cqcc: The index of the component to which this marker segment relates. The components are indexed 0, 1, 2, etc. (Either 8 or 16 bits depending on Csiz value.)

Sqcc: Quantization style for this component.

SPqcc\(^{1}\): Quantization value for each sub-band in the defined order (see Annex D). The number of parameters is the same as the number of sub-bands in the tile-component with the greatest number of decomposition levels.

### Table A.15 – Quantization component parameter values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size (bits)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCC</td>
<td>16</td>
<td>0xFF5D</td>
</tr>
<tr>
<td>Lqcc</td>
<td>16</td>
<td>5-443</td>
</tr>
<tr>
<td>Cqcc</td>
<td>8</td>
<td>0-255; if Csiz &lt; 257</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0-16383; if Csiz ≥ 257</td>
</tr>
<tr>
<td>Sqcc</td>
<td>8</td>
<td>Rec. ITU-T T.800</td>
</tr>
<tr>
<td>SPqcc(^{1})</td>
<td>variable</td>
<td>Rec. ITU-T T.800</td>
</tr>
</tbody>
</table>

### A.2.7 Component registration (CRG), Rec. ITU-T T.800 | ISO/IEC 15444-1 extended

**Function:** Allows specific registration of components with respect to each other. For coding purposes, the samples of components are considered to be located at reference grid points that are integer multiples of XRsiz, YRsiz and ZRsiz (see Annex B). However, this may be inappropriate for rendering the image. The CRG marker segment describes the "center of mass" of each component's samples with respect to the separation. This marker segment has no effect on decoding the codestream.

**NOTE** – This component registration offset is with respect to the image offset (XOisz, YOisz and ZOisz) and the component separation (XRsiz', YRsiz' and ZRsiz'). For example, the horizontal reference grid point for the left most samples of component \( c \) is \( XRsiz' \cdot \frac{XOisz}{XRsiz'} \). (Likewise for the vertical and axial direction.) The horizontal offset denoted in this marker segment is in addition to this offset.

**Usage:** Main header only. Only one CRG may be used in the main header and it is applicable for all tiles.

**Length:** Variable depending on the number of components.

**Figure A.9 – Component registration syntax**

<table>
<thead>
<tr>
<th>CRG</th>
<th>Lcrg</th>
<th>Xerg(^{1})</th>
<th>Yerg</th>
<th>Zerg(^{1})</th>
<th>Xerg(^{a})</th>
<th>Yerg(^{a})</th>
<th>Zerg(^{a})</th>
</tr>
</thead>
</table>

**CRG:** Marker code. Table A.16 shows the size and values of the symbol and parameters for the component registration marker segment.

**Lcrg:** Length of the marker segment in bytes (not including the marker).

**Xerg\(^{1}\):** Value of the horizontal offset, in units of 1/65536 of the horizontal separation XRsiz', for the \( i \)th component. Thus, values range from 0/65536 (sample occupies its reference grid point) to XRsiz' (65535/65536) (just before the next sample's reference grid point). This value is repeated for every component.

**Yerg\(^{1}\):** Value of the vertical offset, in units of 1/65536 of the vertical separation YRsiz', for the \( i \)th component. Thus, values range from 0/65536 (sample occupies its reference grid point) to YRsiz' (65535/65536) (just before the next sample's reference grid point). This value is repeated for every component.

**Zerg\(^{1}\):** Value of the axial offset, in units of 1/65536 of the axial separation ZRsiz', for the \( i \)th component. Thus, values range from 0/65536 (sample occupies its reference grid point) to ZRsiz' (65535/65536) (just before the next sample's reference grid point). This value is repeated for every component.
Table A.16 – Component registration parameter values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size (bits)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRG</td>
<td>16</td>
<td>0xFF63</td>
</tr>
<tr>
<td>Lcrg</td>
<td>16</td>
<td>6-65534</td>
</tr>
<tr>
<td>Xcrg♯</td>
<td>16</td>
<td>0-65535</td>
</tr>
<tr>
<td>Ycrg♯</td>
<td>16</td>
<td>0-65535</td>
</tr>
<tr>
<td>Zcrg♯</td>
<td>16</td>
<td>0-65535</td>
</tr>
</tbody>
</table>


This Recommendation | International Standard requires the presence of the CAP marker segment in the main header, with the Pcap field signalling the use of Rec. ITU-T T.809 | ISO/IEC 15444-10 as described in Rec. ITU-T T.801 | ISO/IEC 15444-2. Table A.17 explains the usage of its associated Ccap♯ parameter for this Recommendation | International Standard.


For this Recommendation | International Standard it is required for the Rsiz field of the SIZ marker segment (see Rec. ITU-T T.801 | ISO/IEC 15444-2) to signal the presence of the CAP marker segment by enabling the second-most-significant bit. This prevents decoders that are unable to correctly handle Rec. ITU-T T.809 | ISO/IEC 15444-10 enabled codestreams from continuing. It is advisable that the CAP marker segment appears immediately after the SIZ marker segment, such that a decoder can easily recognize Rec. ITU-T T.809 | ISO/IEC 15444-10 enabled codestreams before encountering any extended marker segments.

Table A.17 – Ccap♯, extended

<table>
<thead>
<tr>
<th>Values (bits)</th>
<th>Coding style</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 0000 0000 0000 0000</td>
<td>No extended capabilities</td>
</tr>
<tr>
<td>All other values reserved</td>
<td></td>
</tr>
</tbody>
</table>
Annex B

Image and compressed image data ordering, extension

(This annex forms an integral part of this Recommendation | International Standard.)

B.1 Introduction

In this annex and all of its subclauses, the flow charts and tables are normative only in the sense that they are defining an output that alternative implementations shall duplicate. This annex describes the various structural entities, and their organization in the codestream: components, tiles, sub-bands and their divisions.

This annex is the extension of Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex B with volumetric coding functionality, i.e., from two to three spatial dimensions. The following subclauses will describe only the changed items to Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex B that are needed to add the extra axial dimension. Unless explicitly noted, all descriptions and specifications of Rec. ITU-T T.800 | ISO/IEC 15444-1 remain valid.

B.2 Introduction to image data structure concepts


Components no longer consist of two-dimensional-arrays of samples, but instead they consist of three-dimensional-arrays of samples. Each component, \( c \), now has parameters \( XRsiz_c \), \( YRsiz_c \) and \( ZRsiz_c \) which define the mapping between component samples and the reference grid points.

Each resolution level consists of either the \([L|H|X][L|H|X][L|H|X]\) sub-bands (excluding the LLL sub-band) or the \( N_{L}LLL \) sub-band, thus changing the number of sub-bands per decomposition level, \( m \), with \( m < N_{L} \), from three to the range \([2;7]\) (see Figure D.6).

Each sub-band has its own origin. The sub-band boundary conditions are unique for each of the \([L|H|X][L|H|X][L|H|X]\) sub-bands.

B.3 Component mapping to the reference grid


The reference grid becomes a three-dimensional space of points with the indices from \((0, 0, 0)\) to \((Xsiz – 1, Ysiz – 1, Zsiz – 1)\). An "image area" is then defined on the reference grid by the dimensional parameters, \((Xsiz, Ysiz, Zsiz)\) and \((XOsiz, YOsiz, ZOsiz)\). Specifically, the image area on the reference grid is defined by its reference grid points at location \((XOsiz, YOsiz, ZOsiz)\) and \((Xsiz – 1, Ysiz – 1, Zsiz – 1)\).

The samples of component \( c \) are now at integer multiples of \((XRsiz_c, YRsiz_c, ZRsiz_c)\) on the reference grid. Each component domain is a sub-sampled version of the reference grid with the \((0, 0, 0)\) coordinate as common point for each component.

Thus, the samples of component \( c \) are mapped to a cuboid with corner coordinates \((x_0, y_0, z_0)\) and \((x_1 – 1, y_1 – 1, z_1 – 1)\), where \(x_0, y_0, x_1, y_1\) and \(z_0\) are given by Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation B-1 and \(z_1\) is:

\[
\begin{align*}
  z_0 &= \frac{ZOsiz}{ZRsiz_c} \\
  z_1 &= \frac{Zsiz}{ZRsiz_c}
\end{align*}
\]

Thus, the three dimensions of component \( c \) are given by:

\[
(\text{width, height, depth}) = (x_1 – x_0, y_1 – y_0, z_1 – z_0)
\]

The parameters \( Zsiz, ZOsiz \) and \( ZRsiz_c \) are all defined in the NSI marker segment (see A.2.1).

B.4 Image area division into tiles and tile-components

The reference grid is partitioned into a regular sized three dimensional array of tiles. The tile size and tiling offset are defined, on the reference grid, by dimensional pairs \((XT\text{sz}, YT\text{sz}, ZT\text{sz})\) and \((XTO\text{sz}, YTO\text{sz}, ZTO\text{sz})\), respectively. \(ZT\text{sz}\) and \(ZTO\text{sz}\) are parameters from the NSI marker segment.

Every tile is \(XT\text{sz}\) reference grid points wide, \(YT\text{sz}\) reference grid points high and \(ZT\text{sz}\) reference grid points deep. The upper left front corner of the first tile (tile 0) is offset from the upper left front corner of the reference grid by \((XTO\text{sz}, YTO\text{sz}, ZTO\text{sz})\). The tiles are numbered in raster order (i.e., from left to right, top to bottom, front to back). This number is the tile index.

The tile grid offsets \((XTO\text{sz}, YTO\text{sz}, ZTO\text{sz})\) are constrained to be not larger than the image area offsets. This is expressed by Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation B-3 and additionally by the following range:

\[ 0 \leq ZTO\text{sz} \leq ZO\text{sz} \]  

(B-3)

Also, the tile size plus the tile offset shall be greater than the image area offset. This ensures that the first tile (tile 0) will contain at least one reference grid point from the image area. This is expressed by Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation B-4 and additionally by the following range:

\[ ZT\text{sz} + ZTO\text{sz} > ZO\text{sz} \]  

(B-4)

The number of tiles in the horizontal (\(X\)) direction \((numXT\text{tiles})\) and the vertical (\(Y\)) direction \((numYT\text{tiles})\) are given by Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation B-5. The number of tiles for the axial (\(Z\)) direction \((numZ\text{tiles})\) is the following:

\[ numZ\text{tiles} = \left\lfloor \frac{Z\text{sz} - ZTO\text{sz}}{ZT\text{sz}} \right\rfloor \]  

(B-5)

For the purpose of this description, it is useful to have tiles indexed in terms of horizontal, vertical and axial position. Let \(p_x\) be the horizontal index of a tile and \(p_y\) be the vertical index of a tile, then \(p_z\) represents the axial index of a tile, ranging from 0 to \((numZ\text{tiles} - 1)\). The following expression redefines \(p_x\) and \(p_y\) (Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation B-6) and defines \(p_z\):

\[
\begin{align*}
p_x &= \text{mod}\left(\text{mod}(t, numXT\text{tiles} \cdot numYT\text{tiles}), numXT\text{tiles}\right) \\
p_y &= \left\lfloor \frac{\text{mod}(t, numXT\text{tiles} \cdot numYT\text{tiles})}{numXT\text{tiles}} \right\rfloor \\
p_z &= \left\lfloor \frac{t}{numXT\text{tiles} \cdot numYT\text{tiles}} \right\rfloor 
\end{align*}
\]  

(B-6)

As for the coordinates of a particular tile on the reference grid, these are described by the following equations:

\[
\begin{align*}
tx_0(p_x, p_y, p_z) &= \max(XTO\text{sz} + p_x \cdot XT\text{sz}, XO\text{sz}) \\
ty_0(p_x, p_y, p_z) &= \max(YTO\text{sz} + p_y \cdot YT\text{sz}, YO\text{sz}) \\
tz_0(p_x, p_y, p_z) &= \max(ZTO\text{sz} + p_z \cdot ZT\text{sz}, ZO\text{sz}) \\
tx_1(p_x, p_y, p_z) &= \min(XTO\text{sz} + (p_x + 1) \cdot XT\text{sz}, XO\text{sz}) \\
ty_1(p_x, p_y, p_z) &= \min(YTO\text{sz} + (p_y + 1) \cdot YT\text{sz}, YO\text{sz}) \\
tz_1(p_x, p_y, p_z) &= \min(ZTO\text{sz} + (p_z + 1) \cdot ZT\text{sz}, ZO\text{sz}) 
\end{align*}
\]  

(B-7)

Where \(tx_0(p_o, p_o, p_o), ty_0(p_o, p_o, p_o), tz_0(p_o, p_o, p_o)\) and \(tz_0(p_o, p_o, p_o)\) are the coordinates of the upper left front corner of the tile and \(tx_0(p_o, p_o, p_o) - 1, ty_0(p_o, p_o, p_o) - 1\) and \(tz_0(p_o, p_o, p_o) - 1\) are the coordinates of the lower right back corner of the tile. We will often drop the tile's coordinates in referring to a specific tile and refer instead to coordinates \((tx_0, ty_0, tz_0)\) and \((tx_1, ty_1, tz_1)\).

Thus, the dimensions of a tile in the reference grid are:

\[
(tx_1 - tx_0, ty_1 - ty_0, tz_1 - tz_0) 
\]  

(B-8)
Within the domain of image component \( i \), the coordinates of the upper left front hand sample are given by \((tcx_0, tcy_0, tcz_0)\) and the coordinates of the lower right back hand sample are given by \((tcx_1, tcy_1, tcz_1)\), where \(tcx_0, tcy_0, tcx_1\) and \(tcy_1\) are described in Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation B-12 and \(tcz_0\) and \(tcz_1\) are given by the following equation:

\[
  tcz_0 = \left\lfloor \frac{tcz_0}{ZRsz} \right\rfloor \quad tcz_1 = \left\lfloor \frac{tcz_1}{ZRsz} \right\rfloor
\]  

(B-9)

So, the dimensions of the tile-component in the reference grid are:

\[
  (tcx_1 - tcx_0, tcy_1 - tcy_0, tcz_1 - tcz_0)
\]  

(B-10)

### B.5 Transformed tile-component division into resolution levels and sub-bands


NOTE – Although Rec. ITU-T T.809 | ISO/IEC 15444-10 (JP3D) allows a different number of decomposition levels for each of the three dimensions (horizontal denoted by X, vertical denoted by Y and axial denoted by Z), it is fundamentally different from Rec. ITU-T T.801 | ISO/IEC 15444-2 Annex F: "Arbitrary Decomposition of Tile-components". The decomposition of a tile-component described in this Recommendation | International Standard is NOT arbitrary.

Each tile-component is wavelet transformed with \( N_{LX} \) decomposition levels in the horizontal direction, \( N_{LY} \) decomposition levels in the vertical direction and \( N_{LZ} \) decomposition levels in the axial direction as described in Annex D. The direction with the highest number of decomposition levels also determines the number of resolution levels. Thus, with \( N_L = \max(N_{LX}, N_{LY}, N_{LZ}) \) as defined in D.3.2, there are \((N_L + 1)\) distinct resolution levels, denoted \( r = 0, 1, \ldots, N_L \). Each resolution level, \( r \), is represented by the \( n[L][X][L][X] \) band, with \( n = N_L - r \), where the actual sub-band type is determined by the number of decompositions in each of the directions (see D.4.1). For example, when \( N_{LX} = 3, N_{LY} = 3 \) and \( N_{LZ} = 2 \), then at \( r = 0 \), the lowest resolution level is represented by the 3LLX band, while at, \( r = 1 \), the resolution level is represented by the 2LLL band. This clause describes the dimensions of this reduced resolution.

The given tile-component’s coordinates with respect to the reference grid at a particular resolution level, \( r \), yield upper left front hand sample coordinates, \((ttx_0, tty_0, ttz_0)\) and lower right back hand sample coordinates, \((ttx_1, tty_1, ttz_1, \ldots, ttx_{n-1}, tty_{n-1}, ttz_{n-1})\), where:

\[
  ttx_0 = \left\lfloor \frac{tcx_0}{2 \min(N_L - r, N_{LX})} \right\rfloor \quad ttx_1 = \left\lfloor \frac{tcx_1}{2 \min(N_L - r, N_{LX})} \right\rfloor
\]

(B-11)

In a similar manner, the tile coordinates may be mapped into any particular sub-band, \( b \), yielding upper left front hand sample coordinates \((ttx_0, tty_0, ttz_0)\) and lower right back hand sample coordinates \((ttx_{n-1}, tty_{n-1}, ttz_{n-1})\), where:

\[
  ttx_0 = \left\lfloor \frac{tcx_0 - (2^{nx_0 - 1} \cdot xo_b)}{2^{nx_0}} \right\rfloor \quad ttx_1 = \left\lfloor \frac{tcx_1 - (2^{nx_0 - 1} \cdot xo_b)}{2^{nx_0}} \right\rfloor
\]

(B-12)

where \(nx_0, ny_0\) and \(nz_0\), as defined in Equation B-13, represent the respective decomposition levels for the horizontal (X), vertical (Y) and axial (Z) directions associated with sub-band \( b \). The quantities \((xo_b, yo_b, zo_b)\) are given in Table B.1.
\[ n_{xb} = \min(N_L - r + 1, N_{LX}) \]
\[ n_{yb} = \min(N_L - r + 1, N_{LY}) \]
\[ n_{zb} = \min(N_L - r + 1, N_{LZ}) \]  

(B-13)

<table>
<thead>
<tr>
<th>Sub-band type</th>
<th>(xob)</th>
<th>(yob)</th>
<th>(zob)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[L][L][L]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H[L][L][L]</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>[L][L][H]</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>HH[L][L]</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>[L][H][L][L]</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>H[L][H][L]</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>[L][H][H]</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>HHH</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table B.1 – Quantities \((xob, yob, zob)\) for sub-band \(b\)

For each sub-band, these coordinates define the tile boundaries in distinct sub-band domains. Furthermore, the dimensions of each sub-band are given by:

\[(tbx_1 - tbx_0, tby_1 - tby_0, tbz_1 - tbz_0)\]  

(B-14)

\[\text{B.6 Division of resolution levels into precincts}\]


Consider a particular tile-component and resolution level whose bounding sample coordinates in the reduced resolution image domain are \((trx_0, try_0, trz_0)\) and \((trx_{-1}, try_{-1}, trz_{-1})\), as already described. Analogue to the method described in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause B.6, the three-dimensional tile-component resolution level is partitioned into precincts, using \(trx_0, trx_{-1}, try_0\) and \(try_{-1}\), and additionally also \(trz_0\) and \(trz_{-1}\). The precinct is anchored at \((0, 0, 0)\), so that the upper left front hand corner of any given precinct in the partition is located at integer multiples of \((2PPx, 2PPy, 2PPz)\) where \(PPx, PPy, PPz\) are signalled in the COD or COC marker segments. As for \(PPx, PPy, PPz\) may be different for each tile-component and resolution level. \(PPz\) must be at least 1 for all resolution levels, \(r\), except when \(r = 0\) where it is allowed to be zero.

The number of precincts which span the tile-component at resolution level, \(r\), is given by Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation B-16 and by the following equation:

\[\text{numprecinctsdeep} = \begin{cases} 
\left\lfloor \frac{trz_1}{2^{PPz}} \right\rfloor - \left\lfloor \frac{trz_0}{2^{PPz}} \right\rfloor & \text{if } trz_1 > trz_0 \\
0 & \text{if } trz_1 = trz_0 
\end{cases} \]  

(B-15)

Even if Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation B-16 or Equation B-15 of this Recommendation | International Standard indicate that \(\text{numprecinctsdeep}\) are non-zero, some, or all, precincts may still be empty as explained in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause B.6. The precinct index runs from 0 to \(\text{numprecincts} - 1\) where \(\text{numprecincts} = \text{numprecincts\_wide}\times\text{numprecincts\_high}\times\text{numprecincts\_deep}\) in raster order (i.e., from left to right, top to bottom, front to back). The index is used in determining the order of appearance, in the codestream, of packets corresponding to each precinct, as explained in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause B.12.

\[\text{B.7 Division of sub-bands into code-blocks}\]


The sub-bands are partitioned into rectangular 3D code-blocks for the purpose of coefficient modelling and coding. The size of each code-block is determined from three parameters, \(xcb, ycb\) and \(zcb\), which are signalled in the COD or COC marker segments. The code-block size for each sub-band at a particular resolution level is determined as \(2^{xcb'}\) by \(2^{ycb'}\) by \(2^{zcb'}\) where \(xcb', ycb'\) and \(zcb'\) are described by Rec. ITU-T T.800 | ISO/IEC 15444-1 Equations B-17 and B-18 and \(zcb'\) is given by:
\[
zb' = \begin{cases} 
\min(zcb, PPz - 1) & r > 0 \\
\min(zcb, PPz) & r = 0 
\end{cases} \quad (B-16)
\]

These equations reflect the fact that the code-block size is constrained both by the precinct size and the code-block size, whose parameters, \(xcb\), \(ycb\) and \(zcb\), are identical for all sub-bands in the tile-component. Like the precinct, the code-block partition is anchored at \((0, 0, 0)\). Thus, all boundaries of code-blocks in the code-block partition are located at \(x = g_x2^{\delta r'}, y = g_y2^{\delta r'}\) and \(z = g_z2^{\delta r'}\) where \(g_x\), \(g_y\) and \(g_z\) are integers.

### B.8 Packets


All compressed image data representing a specific tile, layer, component, resolution level and precinct appears in the codestream in a contiguous segment called a packet. Packet data is aligned at 8-bit (one byte) boundaries.

As defined in Annex D, resolution level \(r = 0\) contains the sub-band coefficients from the \(N_z\) LLL sub-bands, where \(N_z\) is the number of decomposition levels as defined in clause D.3.2. Each subsequent resolution level, \(r > 0\), contains the sub-band coefficients from the \(n[L|H|X][L|H|X][L|H|X]\) sub-bands, \(n\) LLL excluded, as defined in Annex D, where \(n = N_z - r + 1\). There are \((N_z + 1)\) resolution levels for a tile-component with \(N_z\) decomposition levels.

The compressed image data in a packet is ordered such that the contribution from the LLL, XL, LXX, XLL, XXL, XHL, HXL, HLX, HXX, HHL, HHLX, HXX, LLH, XLH, LH, XHL, HLH, HXL, XLX, XXL sub-bands appear in that order (i.e., Morton scanning order). Within each sub-band, the codeblock contributions appear in raster order, confined to the bounds established by the relevant precinct. Resolution level \(r = 0\) contains only the \(N_z\) LLL band and resolution levels \(r > 0\) can only contain some of the \(N_z[L|H|X][L|H|X][L|H|X]\) bands, excluded \(N_z\) LLL. Only those codeblocks that contain samples from the relevant sub-band, confined to the precinct, have any representation in the packet.

Packet data is introduced by a packet header whose syntax is described in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause B.10 and is followed by a packet body containing the actual code-bytes contributed by each of the relevant code-blocks. The order defined above is followed in constructing both the packet header and the packet body.

### B.9 Packet header information coding


#### B.9.1 Tag trees

Rec. ITU-T T.800 | ISO/IEC 15444-1 clause B.10.2 describes two dimensional tag trees. For the purpose of a three-dimensional extension, three-dimensional tag trees are required.

A 3D tag tree is a way of representing a three-dimensional array of non-negative integers in a hierarchical way. It successively creates reduced resolution levels of this three-dimensional array, forming a tree. At every node of this tree, the minimum integer of the top (up to eight) nodes below is recorded. The notation, \(q_i(m_x, m_y, m_z)\), is the value at the node that is \(m_x\)th from the left, \(m_y\)th from the top and \(m_z\)th from the front, at the \(i\)th level. Level 0 is the lowest level of the tag tree; it contains the top node.

See Rec. ITU-T T.800 | ISO/IEC 15444-1 clause B.10.2 for further information on how to actually encode and decode values with the tag tree. The description given there is independent of the number of actual dimensions.

#### B.9.2 Order of information within a packet


The following is the packet header information order for one packet of a specific layer, tile-component, resolution level and precinct.

- bit for zero or non-zero length packet
- for each subband \([L|H|X][L|H|X][L|H|X]\)
  - for all code-blocks in this subband confined to the relevant precinct, in raster order
    - code-block inclusion bits (if not previously included then tag tree, else one bit)
    - if code-block included:
      - if first instance of code-block
        - zero bit-planes information
      - number of coding passes included
      - increase of code-block length indicator (Lblock)
      - for each codeword segment
        - length of codeword segment
B.10 Progression order


For a given tile-part, the packets contain all compressed image data from a specific layer, a specific component, a specific resolution level, and a specific precinct. The order in which these packets are found in the codestream is called the progression order. The ordering of the packets can progress along four axes: layer, component, resolution level and precinct.

It is possible that components have a different number of resolution levels. In this case, the resolution level that corresponds to the $N_i LLL$ sub-band is the first resolution level ($r = 0$) for all components. The indices are synchronized from that point on.

B.10.1 Progression order determination

This clause describes the algorithms that define the five possible progression orders. They are basically identical to those described in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause B.12.1, but extended to three dimensions. The lines printed in bold indicate the additions necessary for the third dimension.

The COD marker segments signal which of the five progression orders are used (see Rec. ITU-T T.800 | ISO/IEC 15444-1 clause A.6.1). The progression order can also be overridden with the POC marker segment (see Rec. ITU-T T.800 | ISO/IEC 15444-1 clause A.6.6) in any tile-part header. For each of the possible progression orders, the mechanism to determine the order in which packets are included is described below.

B.10.1.1 Layer-resolution level-component-position progression


B.10.1.2 Resolution level-layer-component-position progression


B.10.1.3 Resolution level-position-component-layer progression

Resolution level-position-component-layer progression for three dimensions is defined as the interleaving of the packets in the following order:

\[
\text{for each } r = 0, \ldots, N_{max}, \quad \text{for each } z = t_z, \ldots, t_z - 1, \quad \text{for each } y = t_y, \ldots, t_y - 1, \quad \text{for each } x = t_x, \ldots, t_x - 1, \quad \text{for each } i = 0, \ldots, C_{sz} - 1
\]

\[
\begin{align*}
\text{if } (z \text{ divisible by } 2^{PP_z(r,i) + N_i(r) - r}) \text{ OR } (y \text{ divisible by } 2^{PP_y(r,i) + N_i(r) - r}) \text{ OR } (x \text{ divisible by } 2^{PP_x(r,i) + N_i(r) - r}) \text{ OR } (y + x \text{ divisible by } 2^{PP_y(r,i) + N_i(r) - r}) \text{ OR } (x + y \text{ divisible by } 2^{PP_x(r,i) + N_i(r) - r}) \text{ OR } (x + y + z \text{ divisible by } 2^{PP_z(r,i) + N_i(r) - r}) \\
\text{for the next precinct, } k, \text{ if one exists,}
\end{align*}
\]

packet for component $i$, resolution level $r$, layer $l$, and precinct $k$

In the above, $k$ can be obtained from:

\[
k = \left[ \frac{x}{XRsz(i) \cdot 2^{NL-r}} - \frac{trx_0}{2^{PP_x(r,i)}} \right] + \text{num precinct wide}(r,i) \cdot \left[ \frac{y}{YRsz(i) \cdot 2^{NL-r}} - \frac{try_0}{2^{PP_y(r,i)}} \right]
\]

\[
+ \text{num precinct wide} \cdot \text{num precinct high} \cdot \left[ \frac{z}{ZRsz(i) \cdot 2^{NL-r}} - \frac{trz_0}{2^{PP_z(r,i)}} \right]
\]

To use this progression, $XRsz$, $YRsz$ and $ZRsz$ values must be powers of two for each component.
B.10.1.4 Position-component-resolution level-layer progression

Position-component-resolution level-layer progression is defined as the interleaving of the packets in the following order:

for each $z = tz_0, \ldots, tz_z - 1$,
for each $y = ty_0, \ldots, ty_y - 1$,
for each $x = tx_0, \ldots, tx_x - 1$,
for each $i = 0, \ldots, \text{Csiz} - 1$,
for each $r = 0, \ldots, N_{\text{max}}$, where $N_i$ is the number of decomposition levels for component $i$,
if ($z$ divisible by $2^ZRsiz(i)$) OR (($z = tz_0$) AND (tr$z_0 \cdot 2^ZRsiz(i)$))
if ($y$ divisible by $2^YRsiz(i)$) OR (($y = ty_0$) AND (tr$y_0 \cdot 2^YRsiz(i)$))
if ($x$ divisible by $2^XRsz(i)$) OR (($x = tx_0$) AND (tr$x_0 \cdot 2^XRsz(i)$))

for the next precinct, $k$, if one exists,
for each $l = 0, \ldots, L - 1$
packet for component $i$, resolution level $r$, layer $l$, and precinct $k$

In the above, $k$ can be obtained from Equation B-17. To use this progression, $XRsz$, $YRsiz$ and $ZRsiz$ values must be powers of two for each component.

B.10.1.5 Component-position-resolution level-layer progression

Component-position-resolution level-layer progression is defined as the interleaving of the packets in the following order:

for each $i = 0, \ldots, \text{Csiz} - 1$,
for each $z = tz_0, \ldots, tz_z - 1$,
for each $y = ty_0, \ldots, ty_y - 1$,
for each $x = tx_0, \ldots, tx_x - 1$,
for each $r = 0, \ldots, N_{\text{max}}$, where $N_i$ is the number of decomposition levels for component $i$,
if ($z$ divisible by $2^ZRsiz(i)$) OR (($z = tz_0$) AND (tr$z_0 \cdot 2^ZRsiz(i)$))
if ($y$ divisible by $2^YRsiz(i)$) OR (($y = ty_0$) AND (tr$y_0 \cdot 2^YRsiz(i)$))
if ($x$ divisible by $2^XRsz(i)$) OR (($x = tx_0$) AND (tr$x_0 \cdot 2^XRsz(i)$))

for the next precinct, $k$, if one exists,
for each $l = 0, \ldots, L - 1$
packet for component $i$, resolution level $r$, layer $l$, and precinct $k$

In the above, $k$ can be obtained from Equation B-17.
Annex C

Coefficient bit modelling

(This annex forms an integral part of this Recommendation | International Standard.)

C.1 Introduction

In this annex and all of its subclauses, the flow charts and tables are normative only in the sense that they are defining an output that alternative implementations shall duplicate. This annex formally extends Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex D with volumetric coding functionality.

This annex defines the modelling and scanning of transform coefficient bits.

Code-blocks (see Annex B) are decoded a bit-plane at a time starting from the most significant bit-plane with a non-zero element to the least significant bit-plane. For each bit-plane in a code-block, a special code-block scan pattern is used for each of three coding passes. Each coefficient bit in the bit-plane appears in only one of the three coding passes called significance propagation, magnitude refinement, and cleanup. For each pass contexts are created which are provided to the arithmetic coder, CX, along with the bit stream, CD (see Rec. ITU-T T.800 | ISO/IEC 15444-1 clause C.3).

C.2 Code-block scan pattern within code-blocks, extended

Each bit-plane of a code-block is scanned in a particular order. The 3D code-block is processed in stripes, each consisting of four rows (or all remaining rows if less than four) and spanning the width of the 3D code-block. Each stripe is processed column by column from top to bottom and from left to right. The complete 3D code-block is consequently scanned slice by slice. Within a slice, Rec. ITU-T T.800 | ISO/IEC 15444-1 is followed.

C.3 Context model updates

For the context modelling, the model described in Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex D is modified with respect to the significance propagation and cleanup coding passes.

The context vector for a given current coefficient is the binary vector consisting of the significance states of its 8 nearest-neighbour coefficients in the XY plane, as shown in Rec. ITU-T T.800 | ISO/IEC 15444-1 Figure D.2. Any nearest neighbour lying outside the current coefficient's code-block is regarded as insignificant (i.e., it is treated as having a zero significance state) for the purpose of creating a context vector for decoding the current coefficient.

Rather than using Rec. ITU-T T.800 | ISO/IEC 15444-1 Table D.1, the relevant contexts are specified by Table C.1 below.

### Table C.1 – Contexts for the significance propagation and cleanup coding passes

| Sub-bands with primary orientation of L[L|H][X]|L[H][X], X[L][H|L][H|X] or XX[L][H] | Sub-bands with primary orientation of H[L][X]|L|H[X] | Sub-bands with primary orientation of HH[L][H[X] | Context label\(^{a)}\) |
|---|---|---|---|---|---|
| \(\sum H_i\) | \(\sum V_i\) | \(\sum D_i\) | \(\sum H_i\) | \(\sum V_i\) | \(\sum D_i\) | \(\sum (H_i+V_i)\) | \(\sum D_i\) |
| 2 | \(x\)\(^{b)}\) | \(x\) | 2 | \(x\) | \(x\) | \(\geq 3\) | 8 |
| 1 | \(\geq 1\) | \(x\) | 1 | \(\geq 1\) | \(x\) | \(\geq 1\) | 7 |
| 1 | 0 | \(\geq 1\) | 0 | 1 | \(\geq 1\) | 0 | 2 | 6 |
| 1 | 0 | 0 | 0 | 1 | 0 | \(\geq 2\) | 1 | 5 |
| 0 | 2 | \(x\) | 1 | 0 | \(x\) | 1 | 1 | 4 |
| 0 | 1 | \(x\) | 1 | 0 | \(x\) | 0 | 1 | 3 |
| 0 | 0 | \(\geq 2\) | 0 | 0 | \(\geq 2\) | 0 | 2 | 2 |
| 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

\(^{a)}\) Note that the context labels are indexed only for identification convenience in this Recommendation | International Standard. The actual identifiers used is a matter of implementation.

\(^{b)}\) \(x = \text{"don't care"}\).
Annex D

Discrete wavelet transformation of tile-components

(This annex forms an integral part of this Recommendation | International Standard.)

D.1 Introduction

In this annex and all of its subclauses, the flow charts and tables are normative only in the sense that they define an output that alternative implementations shall duplicate.

This annex describes the three-dimensional forward discrete wavelet transformation applied to one tile-component and specifies the inverse three-dimensional discrete wavelet transformation used to reconstruct the tile-component [3], [4] and [5]. This annex formally extends Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex F with volumetric coding functionality.

D.2 Tile-component parameters

Consider the tile-component defined by the coordinates \( tcx_{0}, tcx_{1}, tcy_{0}, tcy_{1}, tcz_{0} \) and \( tcz_{1} \) given in Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation B-12 and in Equation B-9 of this Recommendation | International Standard. Then the coordinates \( (x,y,z) \) of the tile-component (with sample values \( I(x,y,z) \)) lie in the range defined by:

\[
111 000 \leq x < tcx_{1}, \quad tcy_{0} \leq y < tcy_{1} \quad \text{and} \quad tcz_{0} \leq z < tcz_{1}
\]

(D-1)

D.3 Discrete wavelet transformations

D.3.1 Low-pass and high-pass filtering (informative)


D.3.2 Decomposition levels

Each tile-component is transformed into a set of three-dimensional sub-band signals (called sub-bands), each representing the activity of the signal in various frequency bands, at various spatial resolutions. \( N_{LX} \) denotes the number of decomposition levels in the horizontal direction, \( N_{LY} \) denotes the number of decomposition levels in the vertical direction and \( N_{LZ} \) denotes the number of decomposition levels in the axial direction. For the purpose of this Recommendation | International Standard, we define \( N_L = \max(N_{LX}, N_{LY}, N_{LZ}) \).

D.3.3 Discrete wavelet filters (informative)

See Rec. ITU-T T.800 | ISO/IEC 15444-1 clause F.2.3.

D.4 Inverse discrete wavelet transformation

D.4.1 The IDWT procedure

The inverse discrete wavelet transformation (IDWT) transforms a set of sub-bands, \( a_{i}(u_{i},v_{i},w_{i}) \) into a DC-level shifted tile-component, \( I(x,y,z) \) (IDWT procedure). The IDWT procedure (see Figure D.1) also takes as input the set of parameters \( N_{LX}, N_{LY} \) and \( N_{LZ} \), which represent the number of decomposition levels in each of the three dimensions and are signalled in the COD or COC markers (see A.2.2 and A.2.3).

The sub-bands are labelled in the following way: an index \( \text{lev} \) corresponding to the decomposition level, followed by three letters of which each letter is either L, H or X. Thus a sub-band label is given as \( \text{lev}[L|H|X][L|H|X][L|H|X] \).

Figure D.1 – Inputs and outputs of the IDWT procedure
The sub-band \( b = \text{lev}[L|X][L|X][L|X] \) corresponds to a downsampled version of the sub-band \( (\text{lev} - 1)[L|X][L|X][L|X] \) which has been low-pass filtered for those directions (horizontal, vertical and/or axial) that are denoted by the \( L \) letter. If at decomposition level, \( (\text{lev} - 1) \), a specific direction is not low-pass filtered (i.e., the letter \( X \) was used), it may no longer be low-pass filtered in any of the subsequent higher decomposition levels, \( n > (\text{lev} - 1) \). Thus, when the number of decompositions in direction \( d \) (with \( d \) being either \( X \), \( Y \) or \( Z \)), \( N_{Ld} \), is less than \( \text{lev} \), the decomposition type of that respective dimension is \( X \); otherwise, it is \( L \). The sub-band \( b = 0LLL \) corresponds to the original tile-component.

Similarly to Rec. ITU-T T.800 | ISO/IEC 15444-1 clause F.3.1, the sub-bands are signalled in the codestream, in the order given below:

\[
N_{3LLL}, N_{3XLL}, N_{2LXL}, N_{2XLX}, N_{2XXL}, N_{2HXL}, N_{2HLX}, N_{2HXX}, N_{1LHL}, N_{1XHL},
\]

\[
N_{1HXL}, N_{1XHH}, N_{1LHH}, N_{1XHL}, N_{1HHH}, (N_{L-1})HLL, (N_{L-1})HXL, (N_{L-1})XLX, (N_{L-1})HXX, (N_{L-1})LHXXX, (N_{L-1})LXXH, (N_{L-1})XXLH, (N_{L-1})LXXX, 1XHL, 1HHL, 1HHL, 1LHL, 1LLH, 1LXH, 1XLH, 1XXH, 1XXL, 1HXX, 1LHH, 1LXX, 1XXL, 1HHL, 1HHH.
\]

Note that, from the list of sub-bands given above, only those sub-bands that exist, given the parameters \( N_{LX}, N_{LY} \) and \( N_{LZ} \), will be present in the codestream. These are the exact sub-bands necessary to fully reconstruct the original tile-component.

**Figure D.2 – IDWT procedure**

As in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause F.3.1, the IDWT procedure starts with the initialization of the variable \( \text{lev} \) (the current decomposition level) to \( N_{L} \). The 3D_SR procedure (see D.4.2) is performed at every level \( \text{lev} \), where the level \( \text{lev} \) decreases at each iteration, until \( N_{L} \) iterations are performed. The 3D_SR procedure is iterated over the \( \text{lev}[L|X][L|X][L|X] \) sub-band produced at each iteration.

Finally, the sub-band \( a_{0LLL}(u_{0LLL},v_{0LLL},w_{0LLL}) \) is the output array \( I(x, y, z) \).

As defined in Equation B-12, the indices of sub-band coefficients for a given sub-band \( b \) lie in the range defined by:

\[
tbx_0 \leq u_b < tbx_1, \quad tby_0 \leq v_b < tby_1 \quad \text{and} \quad tbz_0 \leq w_b < tbz_1
\]

**D.4.2 The 3D_SR procedure**

The 3D_SR procedure performs a reconstruction of sub-band \( a_{(\text{lev}-1)[L|X][L|X][L|X]}(u,v,w) \) from the given sub-bands \( a_{(\text{lev})H[X][H|X][H|X]}(u,v,w) \). The total number of coefficients of the reconstructed \( (\text{lev} - 1)[L|X][L|X][L|X] \) sub-band is equal to the sum of the total number of coefficients of the sub-bands used as input to the 3D_SR procedure.
The sub-bands \( a_{lev \mid LX \mid LX \mid LX}(u,v,w) \) are merged into the array \( a(u,v,w) \), using the TO_ARRAY procedure. This temporary array is used to store the intermediate results and is constantly updated as the 3D_SR procedure is executed. Subsequently, the 3D_SR procedure reconstructs each direction, \( d \), for which \( lev < N_{Ld} \leq N_L \), with \( d \) being \( X \), \( Y \) or \( Z \), using the HOR_SR, VER_SR and AXIAL_SR procedures respectively. The end result is the sub-band \( a_{lev-1 \mid LX \mid LX \mid LX}(u,v,w) \). Figure D.4 describes the 3D_SR procedure in detail.

**Figure D.3 – Inputs and outputs of the 3D_SR procedure**

**Figure D.4 – 3D_SR procedure**

### D.4.3 The TO_ARRAY procedure

The TO_ARRAY procedure takes all sub-bands of decomposition level \( lev \) and merges them into a three-dimensional array \( a(u,v,w) \) as shown in Figure D.6. It takes as input the sub-bands \( a_{lev \mid LX \mid LX \mid LX}(u,v,w) \) and the horizontal, vertical and axial extent of the coefficients of sub-band \( a_{lev-1 \mid LX \mid LX \mid LX} \), given as \( u_0, u_1, v_0, v_1, w_0 \) and \( w_1 \). The output array takes the horizontal, vertical and axial extent of the coefficients as indicated by \( u_0 \leq u < u_1, v_0 \leq v < v_1 \) and \( w_0 \leq w < w_1 \).
D.4.4 The 1D_INTERLEAVE procedure

As illustrated in Figure D.7, the 1D_INTERLEAVE procedure interleaves the low-pass and high-pass coefficients of a wavelet transform. It takes as input a one-dimensional signal, $Y(n)$, and rearranges the coefficient values within the signal by interleaving them. The values of $i_0$ and $i_1$ used by the 1D_INTERLEAVE procedure represent the start and the end of the signal respectively. The way the signal is interleaved to form the output is described by the 1D_INTERLEAVE procedure, given in Figure D.8.

Figure D.7 – Parameters of the 1D_INTERLEAVE procedure
D.4.5 The HOR_SR procedure

The HOR_SR procedure performs an interleaving operation and a horizontal sub-band reconstruction of a three-dimensional array of coefficients. It takes as input a three-dimensional array $a(u,v,w)$, the horizontal, vertical, and axial extent of its coefficients as indicated by $u_0 \leq u < u_1$, $v_0 \leq v < v_1$ and $w_0 \leq w < w_1$ (see Figure D.9) and produces as output a horizontally filtered version of the input array, row by row and slice by slice.

As illustrated in Figure D.10, the HOR_SR procedure applies the one-dimensional sub-band reconstruction (1D_SR procedure) to each row of the input array $a(u,v,w)$, and stores the result back in each row.
The VER_SR procedure

The VER_SR procedure performs an interleave operation and a vertical sub-band reconstruction of a three-dimensional array of coefficients. It takes as input a three-dimensional array \(a(u,v,w)\), the horizontal, vertical and axial extent of its coefficients as indicated by \(u_0 \leq u < u_1\), \(v_0 \leq v < v_1\) and \(w_0 \leq w < w_1\) (see Figure D.11) and produces as output a vertically filtered version of the input array, column by column and slice by slice.

As illustrated in Figure D.12, the VER_SR procedure applies the one-dimensional sub-band reconstruction (1D_SR procedure) to each column of the input array \(a(u,v,w)\), and stores the result back in each column.
D.4.7 The AXIAL_SR procedure

The AXIAL_SR procedure performs an interleave operation and an axial sub-band reconstruction of a three-dimensional array of coefficients. It takes as input a three-dimensional array \( a(u,v,w) \), the horizontal, vertical and axial extent of its coefficients as indicated by \( u_0 \leq u < u_1 \), \( v_0 \leq v < v_1 \) and \( w_0 \leq w < w_1 \) (see Figure D.13) and produces as output an axially filtered version of the input array, row by row and column by column.

As illustrated in Figure D.14, the AXIAL_SR procedure applies the one-dimensional sub-band reconstruction (1D_SR procedure) to each depth of the input array \( a(u,v,w) \), and stores the result back in each depth.

Figure D.12 – VER_SR procedure

Figure D.13 – Inputs and outputs of the AXIAL_SR procedure
**D.4.8 The 1D_SR procedure**

The 1D_SR procedure used to perform the sub-band reconstruction is given in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause F.3.6. Also, all subsequent procedures and specifications, needed directly or indirectly by the 1D_SR procedure, are given in Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex F.

**D.5 Forward transformation (informative)**

**D.5.1 The FDWT procedure (informative)**

The forward discrete wavelet transformation (FDWT) transforms DC-level shifted tile-component samples $I(x,y,z)$ into a set of sub-bands with coefficients $a(u,v,w)$ (FDWT procedure). The FDWT procedure (see Figure D.15) also takes as input the number of decomposition levels in each of the three dimensions and are signalled in the COD or COC markers (see A.2.2 and A.2.3).

As in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause F.4.1, the FDWT procedure starts with the initialization of the variable $lev$ (the current decomposition level) to 1 and assigns the three-dimensional array $I(x,y,z)$ to sub-band $a_{0LLL}$ ($u_{0LLL}$, $v_{0LLL}$, $w_{0LLL}$). The 3D_SD procedure (see D.5.2) is performed at every level $lev$, where the level $lev$ increases by one at each iteration, until $N_1$ iterations are performed. The 3D_SD procedure is iterated over the $(lev – 1)[L[X][L[X][L[X]] sub-band produced at each iteration.
The complete FDWT procedure is described in detail in Figure D.16.

Similar to what is described in Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex F, the generated sub-bands are signalled in the codestream in the order given below:

\[
\begin{align*}
&N_L L L, \quad N_L L X, \quad N_L X L, \quad N_L X X, \quad N_X L L, \quad N_X L X, \quad N_X H L, \quad N_X H X, \quad N_X H X, \\
&N_X H L, \quad N_X H X, \quad N_X H X, \quad N_X L L, \quad N_X L X, \quad N_X L X, \quad N_X L X, \quad N_X L X, \quad N_X H H, \\
&(N_L - 1) L L, \quad (N_L - 1) L X, \quad (N_L - 1) X L, \quad (N_L - 1) X L, \quad (N_L - 1) L X, \quad (N_L - 1) X L, \quad (N_L - 1) H L, \\
&(N_L - 1) H L, \quad (N_L - 1) H L, \quad (N_L - 1) L L, \quad (N_L - 1) L L, \quad (N_L - 1) L L, \quad (N_L - 1) L L, \quad (N_L - 1) L L, \quad (N_L - 1) L L.
\end{align*}
\]

Note that, from the list of sub-bands given above, only those sub-bands that exist, given the parameters \(N_{LX}, N_{LY}\) and \(N_{LZ}\), will be present in the codestream. These are the exact sub-bands necessary to fully reconstruct the original tile-component. Also note that \(N_L [L][X][L][X]\) is the only \([L][X][L][X]\) type sub-band that is signalled in the codestream.

![Figure D.15 – Inputs and outputs of the FDWT procedure](image)

**D.5.2 The 3D_SD procedure (informative)**

The 3D_SD procedure performs a decomposition of a three-dimensional array of coefficients or samples \(a_{(u,v,w)}(x,y,z)\) into a number of groups of sub-band coefficients \(a_{lev}(u,v,w)\), depending on the number of decompositions \(N_{LX}, N_{LY}\) and \(N_{LZ}\).

The total number of coefficients of the sub-band \((lev-1)[L][X][L][X]\) is equal to the sum of the total number of coefficients of the sub-bands \(lev[L][X][L][X][L][X]\) resulting from the 3D_SD procedure.

Figure D.17 describes the input and output parameters of the 3D_SD procedure.

![Figure D.16 – FDWT procedure](image)

"Figure D.17 – Inputs and outputs of the 3D_SD procedure"
The 3D_SR procedure (see Figure D.18) decomposes each direction, \( d \), for which \( \text{lev} < N_{d} \leq N_{c} \), with \( d \) being \( X \), \( Y \) or \( Z \), using the HOR_SD, VER_SD and AXIAL_SD procedures respectively. Subsequently, the three-dimensional array \( a(u,v,w) \) is split into the different constructed sub-bands \( a_{\text{lev}[L|X][L|X][L|X]}(u,v,w) \). Of these sub-bands, the \( \text{lev}[L|X][L|X][L|X] \) sub-band is used in the next iteration of the FDWT procedure for further decomposition (as long as less than \( N_{c} \) iterations occurred). The other sub-bands are further processed for signalling in the codestream.

**Figure D.18 – 3D_SD procedure**

**D.5.3 The TO_SUBBANDS procedure (informative)**

The TO_SUBBANDS procedure takes a three-dimensional array \( a(u,v,w) \) as input and returns the sub-bands as indicated in Figure D.6 as output. The array \( a(u,v,w) \) has the horizontal, vertical and axial extent of the coefficients as indicated by \( u_{0} \leq u < u_{1}, \ v_{0} \leq v < v_{1} \) and \( w_{0} \leq w < w_{1} \).

**D.5.4 The AXIAL_SD procedure (informative)**

The AXIAL_SD procedure performs an axial sub-band decomposition of a three-dimensional array of coefficients. It takes as input a three-dimensional array \( a(u,v,w) \), the horizontal, vertical and axial extent of its coefficients as indicated by \( u_{0} \leq u < u_{1}, \ v_{0} \leq v < v_{1} \) and \( w_{0} \leq w < w_{1} \) (see Figure D.19) and produces as output an axially filtered version of the input array, row by row and column by column. After the decomposition, a deinterleave operation is performed.

As illustrated in Figure D.20, the AXIAL_SD procedure applies the one-dimensional sub-band decomposition (1D_SD procedure) to each depth of the input array \( a(u,v,w) \), and stores the result back in each depth.

**Figure D.19 – Inputs and outputs of the AXIAL_SD procedure**
D.5.5 The VER_SD procedure (informative)

The VER_SD procedure performs a vertical sub-band decomposition of a three-dimensional array of coefficients. It takes as input a three-dimensional array \( a(u,v,w) \), the horizontal, vertical and axial extent of its coefficients as indicated by \( u_0 \leq u < u_1 \), \( v_0 \leq v < v_1 \) and \( w_0 \leq w < w_1 \) (see Figure D.21) and produces as output a vertically filtered version of the input array, column by column and slice by slice. After the decomposition, a deinterleave operation is performed.

As illustrated in Figure D.22, the VER_SD procedure applies the one-dimensional sub-band decomposition (1D_SD procedure) to each column of the input array \( a(u,v,w) \), and stores the result back in each column.
D.5.6 The HOR_SD procedure (informative)

The HOR_SD procedure performs a horizontal sub-band decomposition of a three-dimensional array of coefficients. It takes as input a three-dimensional array \( a(u,v,w) \), the horizontal, vertical and axial extent of its coefficients as indicated by \( u_0 \leq u < u_1 \), \( v_0 \leq v < v_1 \) and \( w_0 \leq w < w_1 \) (see Figure D.23) and produces as output a horizontally filtered version of the input array, row by row and slice by slice. After the decomposition, a deinterleave operation is performed.

As illustrated in Figure D.24, the HOR_SD procedure applies the one-dimensional sub-band decomposition (1D_SD procedure) to each row of the input array \( a(u,v,w) \), and stores the result back in each row.
D.5.7 The 1D_DEINTERLEAVE procedure (informative)

As illustrated in Figure D.25, the 1D_DEINTERLEAVE procedure deinterleaves the low-pass and high-pass coefficients of a wavelet transform. It takes as input a one-dimensional signal, \( X(n) \), and rearranges the coefficient values within the signal by deinterleaving them. The values of \( i_0 \) and \( i_1 \) used by the 1D_DEINTERLEAVE procedure represent the start and the end of the signal respectively. The way the signal is deinterleaved to form the output is described by the 1D_DEINTERLEAVE procedure, given in Figure D.26.

Figure D.25 – Parameters of the 1D_DEINTERLEAVE procedure
D.5.8 The 1D_SD procedure (informative)

The 1D_SD procedure used to perform the sub-band decomposition is given in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause F.4.6. Also, all subsequent procedures and specifications, needed directly or indirectly by the 1D_SD procedure, are given in Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex F.
Annex E

Quantization

(This annex forms an integral part of this Recommendation | International Standard.)

E.1 Introduction

In this annex and all of its subclauses, the flow charts and tables are normative only in the sense that they define an output that alternative implementations shall duplicate. This annex specifies the aspects relating to quantization of tile-component transform coefficients. Quantization aspects are specified as in Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex E, but are extended to define quantization with the three-dimensional decompositions described in this Recommendation | International Standard.

E.2 Inverse quantization procedure modifications

The inverse quantization procedure shall be the same as specified in Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex E, except as modified herein in order to accommodate the three-dimensional decomposition structures of this Recommendation | International Standard.

The sub-band types are as specified in Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex E, except that more sub-band types exist for three-dimensional decompositions (i.e., [L|X|H][L|X|H][L|X|H] with XXX excluded).

Sub-band gains are specified by Table E.1 below, rather than as in Table E.1 of Rec. ITU-T T.800 | ISO/IEC 15444-1.

<table>
<thead>
<tr>
<th>Sub-band b type</th>
<th>gain_b</th>
<th>log_2(gain_b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLL, LXX, XLX, XXL, LXL, LLX, XLL</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>H[L</td>
<td>X][L</td>
<td>X], [L</td>
</tr>
<tr>
<td>HH[L</td>
<td>X], H[L</td>
<td>X]H, [L</td>
</tr>
<tr>
<td>HHH</td>
<td>8</td>
<td>3</td>
</tr>
</tbody>
</table>

For three-dimensional decomposition structures as defined in this Recommendation | International Standard, the value \( n_b \) in Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation E-5 denotes the maximum of the number of decomposition levels in each spatial direction from the original tile-component to the sub-band \( b \) (i.e., \( n_b = \max(n_{xb}, n_{yb}, n_{zb}) \), where \( n_{xb}, n_{yb} \) and \( n_{zb} \) are defined by Equation B-13).
Annex F

Coding of images with regions-of-interest, extension

(This annex forms an integral part of this Recommendation | International Standard.)

F.1 Introduction

In this annex and all of its subclauses, the specifications are normative only in the sense that they define an output that alternative implementations shall duplicate. This annex describes the volumetric extension of region-of-interest coding to both Rec. ITU-T T.800 | ISO/IEC 15444-1 Annex H and Rec. ITU-T T.801 | ISO/IEC 15444-2 Annex L.

This annex describes three-dimensional region-of-interest (ROI) technology. An ROI is a part of an image that is encoded with higher fidelity than the rest of the image (the background). The encoding is also done in such a way that the information associated with the ROI precedes the information associated with the background.

F.2 Decoding of ROI

The procedures specified in this clause are applied only in the case of the presence of a RGN marker segment (see A.2.4), indicating the presence of a ROI coded with the Maxshift or the Scaling based method.

F.2.1 Decoding of ROI with the Maxshift method

The procedure realigns the significant bits of ROI coefficients and background coefficients. It is defined using the following steps:

1) Get the scaling value, s, from the SPrgn parameter of the RGN marker segment in the codestream (see A.2.4). The following steps (2, 3 and 4) are applied to each coefficient of sub-band *b*.

2) If \( N_b(u,v,w) < M_b \) (see definitions of \( N_b \) in Rec. ITU-T T.800 | ISO/IEC 15444-1 clause D.2.1 and of \( M_b \) in Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation E-2), then no modification takes place.

3) If \( N_b(u,v,w) \geq M_b \) and if at least one of the first \( M_b \) MSBs \( i = 1,..., M_b \) is non-zero, then the value of \( N_b(u,v,w) \) is updated as \( N_b(u,v,w) = M_b \).

4) If \( N_b(u,v,w) \geq M_b \) and if all first \( M_b \) MSBs are equal to zero, then the following modifications are made:
   a) discard the first \( s \) MSBs and shift the remaining MSBs \( s \) places, as described in Equation F-1, for \( i = 1,..., M_b \).
   b) update the value of \( N_b(u,v,w) \) as given in the following equation:

   \[
   (F-1) \quad MSB_i(b,u,v,w) = \begin{cases} 
   MSB_{i+s}(b,u,v,w) & i + s \leq N_b(u,v,w) \\
   0 & i + s > N_b(u,v,w)
   \end{cases}
   \]

   \[
   (F-2) \quad N_b(u,v,w) = \max(0, N_b(u,v,w) - s)
   \]

F.2.2 Decoding of ROI with the Scaling method

The procedure realigns the significant bits of ROI coefficients and background coefficients. It is defined using the following steps:

1) Get the corresponding shape information and the scaling value, s, from the RGN marker segment for each ROI. Then, steps 2 to 6 are applied to each coefficient \((u,v,w)\) of sub-band *b*.

2) Generate the ROI mask \( \{M_i(u,v,w)\} \) for all ROI, see F.4.2 for details on how to generate the ROI mask.

3) For each coding block, find the largest scaling value, \( s_{\text{max}} \), for any coefficient \((u,v,w)\).

4) For each coefficient in each coding block, find the highest scaling value and set \( s(u,v,w) \) to:

   \[
   (F-3) \quad s(u,v,w) = s_{\text{max}} - \max(s_i \cdot M_i(u,v,w))
   \]

   where \( i = 0...(\text{Number of ROI} - 1) \).
ISO/IEC 15444-10:2011 (E)

5) For each coefficient \((u,v,w)\), discard the first \(s(u,v,w)\) MSBs and shift up the remaining MSBs \(s(u,v,w)\) places, as described in Equation F-4, for \(i = 1, \ldots, M_b\):

\[
\text{MSB}_i(b,u,v,w) = \begin{cases} 
\text{MSB}_{i + s}(u,v,w) & i + s(u,v,w) \leq N_b(u,v,w) \\
0 & i + s(u,v,w) > N_b(u,v,w)
\end{cases}
\]  

(F-4)

6) Update the value of \(N_b(u,v,w)\) as given in Equation F-5:

\[
N_b(u,v,w) = \max\left(0, N_b(u,v,w) - s(u,v,w)\right)
\]  

(F-5)

F.3 Encoding with ROI (informative)

This clause describes how to encode an image with one or more ROIs, using either the Maxshift or the Scaling based method. The encoding is given here as an informative section. At the encoder side, an ROI mask is created describing which quantized transformation coefficients must be encoded with better quality (up to lossless). The ROI mask is a bit map describing these coefficients.

F.3.1 Description of the Maxshift method (informative)

The quantized transform coefficients outside of the ROI mask, called background coefficients, are scaled down so that the bits associated with the ROI are placed in higher bit-planes than the background. This means that when the entropy coder encodes the quantized transform coefficients, the bit-planes associated with the ROI are coded before the information associated with the background. For the ROI mask generation with the Maxshift method, see F.4.1.

The Maxshift method can be described using the following steps:

1) Generate the ROI mask, \(M(x, y, z)\), see F.4.1.
2) Find the scaling value \(s\) (see F.3.2).
3) Add \(s\) LSBs to each coefficient \(|q_b(u,v,w)|\). The number \(M'_b\) of magnitude bit-planes will then be:

\[
M'_b = M_b + s
\]  

(F-6)

where \(M_b\) is given by Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation E-2 and the new value of each coefficient is given by:

\[
|q'_b(u,v,w)| = |q_b(u,v,w)| \cdot 2^s
\]  

(F-7)

4) Scale down all background coefficients given by \(M(x,y,z)\) using the scaling value \(s\) (see F.3.2). Thus, if \(|q_b(u,v,w)|\) is a background coefficient given by \(M(x, y, z)\), then:

\[
|q'_b(u,v,w)| = \frac{|q_b(u,v,w)|}{2^s}
\]  

(F-8)

5) Write the scaling value \(s\) into the codestream using the SPrgn parameter of the RGN marker segment.

After these steps, the quantized transform coefficients are entropy coded as usual.

F.3.2 Selection of scaling value, \(s\), for Maxshift method at encoder side (informative)

The scaling value, \(s\), may be chosen so that Equation F-9 holds, where \(\max(M_b)\) is the largest number of magnitude bit-planes (see Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation E-1), for any background coefficient, \(q_{BG}(x,y,z)\), in any code-block in the current component.

\[
s \geq \max(M_b)
\]  

(F-9)

This guarantees that the scaling value used will be sufficiently large to ensure all the significant bits associated with the ROI will be in higher bit-planes than all the significant bits associated with the background.
F.3.3 Description of the Scaling-based method (informative)

As stated in the introduction part of F.3, the description of encoding with ROI is informative. However, when using the Scaling based ROI method, failure to generate the correct ROI mask at the encoder side will greatly reduce the quality of the decoded image and will not allow lossless decoding. For the ROI mask generation with the Scaling based method, see F.4.2.

The quantized transformation coefficients are scaled in such a manner that the relative significance of each transformation coefficient is equal to the specified scaling value, s, of the ROI to which it applies. If a transformation coefficient belongs to several ROIs, the largest s value is chosen. If a transformation coefficient belongs to the background, the scaling value s equals 0. Before scaling the quantized transformation coefficients of one code-block, the highest, \( s_{\text{Max}} \) and lowest, \( s_{\text{Min}} \) scaling values for the coding block are found.

Consider a quantized transformation coefficient, \( q_b(u,v,w) \), in the current coding block with a corresponding scaling value, s (where \( s_{\text{Min}} \leq s \leq s_{\text{Max}} \)). After scaling, the individual bits of \( q_b(u,v,w) \) end up \( \text{abs}(s_{\text{Max}} - s) \) bit-planes lower than the corresponding bits of a coefficient with \( s = s_{\text{Max}} \). The number of magnitude bits for this coding block will hence increase by \( (s_{\text{Max}} - s_{\text{Min}}) \).

Since the coding blocks are treated independently, quantized transformation coefficients belonging to the same ROI might end up having different levels of significance in different coding blocks. This difference between coding blocks must be taken into account by the rate allocator. An example of this would be if an entire coding block belongs to the image background and another coding block has both ROI and background coefficients. In this case, the background coefficients in the second coding block would be downshifted by \( s_0 \) steps, whereas in the first coding block no shifting would be done. In this case, it is up to the rate allocation algorithm to make sure that the bit-planes from the two coding blocks are put in the bit stream in the correct order.

When the entropy coder encodes the quantized transformation coefficients, the bit-planes associated with the ROI are coded before or at the same time as the information associated with the background. The scaling value, \( s_0 \), for each ROI is specified by the user or application.

The method can be described using the following steps for a set of n ROIs:

- For each coding block in each component:
  1) Generate ROI mask for all ROI \( i \), \( \{M_i(u,v,w)\} \), see F.4.2.
  2) Find \( s_{\text{Min}} \) and \( s_{\text{Max}} \), where \( s_{\text{Min}} \) and \( s_{\text{Max}} \) are the smallest and largest scaling values in the current coding block, respectively.
  3) Add \( s_{\text{Block}} = s_{\text{Max}} - s_{\text{Min}} \) LSBs to each coefficient \( |q_b(u,v,w)| \). The number \( M'_b \) of magnitude bit-planes for sub-band, b, will then be:

\[
M'_b = M_b + s_{\text{Block}}
\]

(F-10)

where \( M_b \) is given by Rec. ITU-T T.800 | ISO/IEC 15444-1 Equation E-2 and the new value of each coefficient is given by:

\[
|q_b(u,v,w)| = |q_b(u,v,w)| \cdot 2^{s_{\text{Block}}}
\]

(F-11)

4) For each coefficient in each coding block, find the highest scaling value and set \( s(u,v,w) \) to:

\[
s(u,v,w) = s_{\text{Max}} - \max(s_i - M_i(u,v,w))
\]

(F-12)

where \( i = 0 \ldots (\text{Number of ROI} - 1) \).

5) Scale down all coefficients so that:

\[
|q_b(u,v,w)| = \frac{|q_b(u,v,w)|}{2^{s(u,v,w)}}
\]

(F-13)

6) For each ROI write the scaling value, s, shape, and reference points into the codestream using the RGN marker segment as described in A.2.4.
F.4 Region-of-interest mask generation

To achieve an ROI with better quality than the rest of the image while maintaining a fair amount of compression, bits need to be saved by sending less information for the background. To do this, an ROI mask is calculated. The mask is a bit-plane indicating a set of quantized transformation coefficients whose coding is sufficient in order for the receiver to reconstruct the desired region with better quality than the background (up to lossless).

To illustrate the concept of ROI mask generation, let us restrict ourselves to a single ROI and a single volume component, and identify the samples that belong to the ROI in the volume domain by a binary mask, \( M(x, y, z) \), where:

\[
M(x, y, z) = \begin{cases} 
1 & \text{wavelet coefficient } (x, y, z) \text{ is needed} \\
0 & \text{accuracy on } (x, y, z) \text{ can be sacrificed without affecting ROI}
\end{cases}
\]  

(F-14)

The mask is a map of the ROI in the wavelet domain so that it has a non-zero value inside the ROI and 0 outside. In each step, each sub-band of the mask is then updated in a raster scan order. The mask will then indicate which coefficients are needed at this step so that the inverse transformation will reproduce the coefficients of the previous mask.

For example, the last step of the inverse transformation is a composition of two sub-bands into one. Then to trace this step backwards, the coefficients of both sub-bands that are needed are found. The step before that is a composition of four sub-bands into two. To trace this step backwards, the coefficients in the four sub-bands that are needed to give a perfect reconstruction of the coefficients included in the mask for two sub-bands are found. Again, the step before that is a composition of eight sub-bands into four. Once again, to trace this step backwards, the coefficients in the eight sub-bands that are needed for all four sub-bands are found.

All steps are then traced backwards to give the mask. If the coefficients corresponding to the mask are transmitted and received, and the inverse transformation calculated on them, the desired ROI will be reconstructed with better quality than the rest of the volume (up to lossless if the ROI coefficients were coded losslessly).

F.4.1 Region-of-interest mask generation for Maxshift method (informative)

Below is a description of how the expansion of the mask is acquired from the various filters. Similar methods can be used for other filters.

F.4.1.1 Region-of-interest mask generation using the 5-3 reversible filter (informative)

In order to get the optimal set of quantized coefficients to be scaled, the following equations described in this clause should be used.

To see what coefficients need to be in the mask, the inverse wavelet transformation is studied. Rec. ITU-T T.800 § ISO/IEC 15444-1 Equations F-5 and F-6 give the coefficients needed to reconstruct \( X(2n) \) and \( X(2n+1) \) losslessly. It can immediately be seen that these are \( L(n) \), \( L(n+1) \), \( H(n-1) \), \( H(n) \), \( H(n+1) \) (see Rec. ITU-T T.800 § ISO/IEC 15444-1 Figure H.1). Hence if \( X(2n) \) and \( X(2n+1) \) are in the ROI, the listed low and high sub-band coefficients are in the mask. Notice that \( X(2n) \) and \( X(2n+1) \) are even and odd indexed points respectively, relative to the origin of the reference grid.

F.4.1.2 Region-of-interest mask generation using the 9-7 irreversible filter (informative)

Successful decoding does not depend upon the selection of samples to be scaled. In order to get the optimal set of quantized coefficients to be scaled, the following equations described in this clause should be used.

To see what coefficients need to be in the mask, the inverse wavelet transformation is studied as in Rec. ITU-T T.800 § ISO/IEC 15444-1 clause H.3.1.1. This is illustrated in Figure H.2. \( X(2n) \) and \( X(2n+1) \) are even and odd indexed points respectively, related to the origin of the reference grid.

The coefficients needed to reconstruct \( X(2n) \) and \( X(2n+1) \) losslessly can immediately be seen to be \( L(n-1) \) to \( L(n+2) \) and \( H(n-2) \) to \( H(n+2) \). Hence if \( X(2n) \) and \( X(2n+1) \) are in the ROI, those low and high sub-band coefficients are in the mask.

F.4.2 Region-of-interest mask generation for Scaling-based method

Below are descriptions of how the expansion of the mask is acquired in the cuboidal and ellipsoidal case and also how this is done for the various filters. Similar methods can be used for other filters.
F.4.2.1 Cuboidal mask generation on the reference grid

The cuboidal mask described in this clause is generated on the reference grid. When generated on the reference grid, the method described in F.4.2.3 is used for mask generation in the wavelet domain. A cuboid is described by six parameters, see Figure F.1, all signalled in the RGN marker (see A.2.4). The parameters are \((XArgn, YArgn, ZArgn, XBrgn, YBrgn, ZBrgn)\), where \(XArgn, YArgn\) and \(ZArgn\) are the \(x, y\) and \(z\) offset of the upper left front corner of the cuboid from the reference grid origin, whereas \(XBrgn, YBrgn\) and \(ZBrgn\) are the \(width\), the \(height\) and the \(depth\) of the cuboid respectively.

The correct mask for the reference grid is given by Equation F-15.

\[
\begin{align*}
XArgn & \leq x \leq XArgn + XBrgn \\
YArgn & \leq y \leq YArgn + YBrgn \\
ZArgn & \leq z \leq ZArgn + ZBrgn
\end{align*}
\]  

(F-15)

Figure F.1 – Cuboid mask on the reference grid

F.4.2.2 Ellipsoidal mask generation on the reference grid

The ellipsoidal mask described in this clause is generated on the reference grid. When generated on the reference grid, the method described in F.4.2.3 is used for mask generation in the wavelet domain. An ellipsoid is described by six parameters, see Figure F.2, all signalled in the RGN marker (see A.2.4). The parameters are \((XArgn, YArgn, ZArgn, XBrgn, YBrgn, ZBrgn)\), where \(XArgn, YArgn\) and \(ZArgn\) are the \(x, y\) and \(z\) offset of the centre of the ellipsoid from the reference grid origin, whereas \(XBrgn, YBrgn\) and \(ZBrgn\) are the \(width\), the \(height\) and the \(depth\) of the ellipsoid respectively.

The correct mask for the reference grid is given by Equation F-16.

\[
\frac{(x - XArgn)^2}{XBrgn^2} + \frac{(y - YArgn)^2}{YBrgn^2} + \frac{(z - ZArgn)^2}{ZBrgn^2} \leq 1
\]  

(F-16)

Figure F.2 – Ellipsoidal mask on the reference grid
F.4.2.3 Fast generation of a cuboidal mask (informative)

In the case of a cuboidal ROI, the mask can be derived more quickly than for arbitrary shapes. In this case, instead of tracing how each coefficient and voxel value is reconstructed in the inverse transform, only two positions need to be studied, namely the upper left front and the lower right back corners of the mask. The front-top-left corner \((x_1, y_1, z_1)\) on the reference grid will be given in the RGN marker segment as \((XArgn, YArgn, ZArgn)\), whereas the rear-bottom-right corner \((x_2, y_2, z_2)\) on the reference grid will be given by the parameters in the RGN marker segment as \((XArgn + XBrgn - 1), (YArgn + YBrgn - 1), (ZArgn + ZBrgn - 1)\).

The mask generation must take into account what type of filter has been used by the transform.

In each level of decomposition, the steps described in the previous clause are followed to see how the mask expands. Let the 1D mask, to be decomposed, be \(R_{ext}\) and let \(x_1\) and \(x_2\) be the lowest and highest indices of non-zero samples in \(R_{ext}\).

1) For each lifting step \(s\) where \(s\) ranges from 0 to \(N_{LS} - 1:\)
   i) Find the lowest sample index \((2n + m_s \geq x_1)\) that is in the mask
      \[
      x'_1 = 2n + 1 - m_s + 2\text{off}_s
      \]  \(\text{(F-17)}\)
      \[
      \text{if } (x'_1 > x_1) \text{ then } x'_1 = x_1
      \]  \(\text{(F-18)}\)
   ii) Find the highest sample index \((2n + m_s \leq x_2)\)
      \[
      x'_2 = 2n + 1 - m_s + 2(L_s - 1 + \text{off}_s)
      \]  \(\text{(F-19)}\)
      \[
      \text{if } (x'_2 > x_2) \text{ then } x'_2 = x_2
      \]  \(\text{(F-20)}\)
   iii) Set \(x_1 = x'_1, x_2 = x'_2\) where \(m_s = 1 - m_{s-1}\) indicates whether the \(s\)th lifting step applies to even-indexed coefficients \((m_s = 0)\) or odd-indexed coefficients \((m_s = 1)\), and where \(L_s\) is the number of lifting coefficients for lifting step \(s\).

Let all samples between \(x_1\) and \(x_2\), inclusive, be non-zero and then separate the ROI mask samples into sub-bands the same way as the wavelet coefficients are separated in using the deinterleave procedure described in F.4.5 of Rec. ITU-T T.800 | ISO/IEC 15444-1.

F.5 Remarks on region-of-interest coding

F.5.1 Usage of Scaling and Maxshift methods

The Maxshift method must not be used together with the Scaling-based method and vice versa.

F.5.2 Multi-component remark (informative)

For the case of colour images, the method applies separately in each colour component. If some of the colour components are down-sampled, the mask for the down-sampled components is created in the same way as the mask of the non-down-sampled components.

F.5.3 Implementation precision remark (informative)

This ROI coding method might in some cases create situations where the dynamic range is exceeded. This is, however, easily solved by simply discarding the least significant bit-planes that exceed the limit due to the downscaling operation. The effect will be that the ROI will have better quality compared to the background, even though the entire bit stream is decoded. It might however create problems when the image is coded with ROI in a lossless mode. Discarding least significant bit-planes for the background might have the result that the background is not coded losslessly, and in the worst case the background may not be reconstructed at all. This depends on the dynamic range available.
Annex G

Examples and guidelines, extensions

(This annex does not form an integral part of this Recommendation | International Standard.)

G.1 Rate-distortion modelling

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