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METHOD, APPARATUS AND SYSTEM FOR ENCODING AND DECODING A BLOCK OF VIDEO SAMPLES

Abstract

A method of decoding coding units of a coding tree for an image frame from a video bitstream comprising splitting a region of the coding tree into a plurality of coding blocks, each of the coding blocks including a prediction block. Determining matrix intra prediction flags for the prediction block of each of the coding blocks, the determination based upon (i) an area of the region if the region meets a threshold, or (ii) a budget for the region if the area of the region does not meet the threshold. The method further comprises reading matrix coefficients from a memory for each prediction block determined to use matrix intra prediction according to the determined flag; and decoding the coding units using prediction blocks generated for each coding unit in the region using reference samples of each prediction block and the matrix coefficients.

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Background/Summary

REFERENCE TO RELATED APPLICATION(S) [0001] This application is a continuation of U.S. patent application Ser. No. 17/620,390, filed on Dec. 17, 2021, which is the National Phase application of PCT Application No. PCT/AU2020/050373 filed on Apr. 15, 2020, and titled “METHOD, APPARATUS AND SYSTEM FOR ENCODING AND DECODING A BLOCK OF VIDEO SAMPLES”. This application claims the benefit under 35 U.S.C. § 119 of the filing date of Australian Patent Application No. 2019204437, filed Jun. 24, 2019. Each of the above-cited patent applications is hereby incorporated by reference in its entirety as if fully set forth herein.

TECHNICAL FIELD

[0002] The present invention relates generally to digital video signal processing and, in particular, to a method, apparatus and system for encoding and decoding a block of video samples. The present invention also relates to a computer program product including a computer readable medium having recorded thereon a computer program for encoding and decoding a block of video samples.

BACKGROUND

[0003] Many applications for video coding currently exist, including applications for transmission and storage of video data. Many video coding standards have also been developed and others are currently in development. Recent developments in video coding standardisation have led to the formation of a group called the “Joint Video Experts Team” (JVET). The Joint Video Experts Team (JVET) includes members of Study Group 16, Question 6 (SG16/Q6) of the Telecommunication Standardisation Sector (ITU-T) of the International Telecommunication Union (ITU), also known as the “Video Coding Experts Group” (VCEG), and members of the International Organisations for Standardisation/International Electrotechnical Commission Joint Technical Committee 1/Subcommittee 29/Working Group 11 (ISO/IEC JTC1/SC29/WG11), also known as the “Moving Picture Experts Group” (MPEG).

[0004] The Joint Video Experts Team (JVET) issued a Call for Proposals (CfP), with responses analysed at its 10.sup.th meeting in San Diego, USA. The submitted responses demonstrated video compression capability significantly outperforming that of the current state-of-the-art video compression standard, i.e.: “high efficiency video coding” (HEVC). On the basis of this outperformance it was decided to commence a project to develop a new video compression standard, to be named ‘versatile video coding’ (VVC). VVC is anticipated to address ongoing demand for ever-higher compression performance, especially as video formats increase in capability (e.g., with higher resolution and higher frame rate) and address increasing market demand for service delivery over WANs, where bandwidth costs are relatively high. At the same time, VVC must be implementable in contemporary silicon processes and offer an acceptable trade-off between the achieved performance versus the implementation cost (for example, in terms of silicon area, CPU processor load, memory utilisation and bandwidth).

[0005] Video data includes a sequence of frames of image data, each of which include one or more colour channels. Generally, one primary colour channel and two secondary colour channels are needed. The primary colour channel is generally referred to as the ‘luma’ channel and the secondary colour channel(s) are generally referred to as the ‘chroma’ channels. Although video data is typically displayed in an RGB (red-green-blue) colour space, this colour space has a high degree of correlation between the three respective components. The video data representation seen by an encoder or a decoder is often using a colour space such as YCbCr. YCbCr concentrates luminance, mapped to ‘luma’ according to a transfer function, in a Y (primary) channel and chroma in Cb and Cr (secondary) channels. Moreover, the Cb and Cr channels may be sampled spatially at a lower rate (subsampling) compared to the luma channel, for example half horizontally and half vertically-known as a ‘4:2:0 chroma format’. The 4:2:0 chroma format is commonly used in ‘consumer’ applications, such as internet video streaming, broadcast television, and storage on Blu-Ray™ disks. Subsampling the Cb and Cr channels at half-rate horizontally and not subsampling vertically is known as a ‘4:2:2 chroma format’. The 4:2:2 chroma format is typically used in professional applications, including capture of footage for cinematic production and the like. The higher sampling rate of the 4:2:2 chroma format makes the resulting video more resilient to editing operations such as colour grading. Prior to distribution to consumers, 4:2:2 chroma format material is often converted to the 4:2:0 chroma format and then encoded for distribution to consumers. In addition to chroma format, video is also characterised by resolution and frame rate. Example resolutions are ultra-high definition (UHD) with a resolution of 3840×2160 or ‘8K’ with a resolution of 7680×4320 and example frame rates are 60 or 120 Hz. Luma sample rates may range from approximately 500 mega samples per second to several giga samples per second. For the 4:2:0 chroma format, the sample rate of each chroma channel is one quarter the luma sample rate and for the 4:2:2 chroma format, the sample rate of each chroma channel is one half the luma sample rate.

[0006] The VVC standard is a ‘block based’ codec, in which frames are firstly divided into a square array of regions known as ‘coding tree units’ (CTUs). CTUs generally occupy a relatively large area, such as 128×128 luma samples. However, CTUs at the right and bottom edge of each frame may be smaller in area. Associated with each CTU is a ‘coding tree’ for the luma channel and an additional coding tree for the chroma channels. A coding tree defines a decomposition of the area of the CTU into a set of blocks, also referred to as ‘coding blocks’ (CBs). It is also possible for a single coding tree to specify blocks both for the luma channel and the chroma channels, in which case the collections of collocated coding blocks are referred to as ‘coding units’ (CUs), i.e., each CU having a coding block for each colour channel. The CBs are processed for encoding or decoding in a particular order. As a consequence of the use of the 4:2:0 chroma format, a CTU with a luma coding tree for a 128×128 luma sample area has a corresponding chroma coding tree for a 64×64 chroma sample area, collocated with the 128×128 luma sample area. When a single coding tree is in use for the luma channel and the chroma channels, the collections of collocated blocks for a given area are generally referred to as ‘units’, for example the above-mentioned CUs, as well as ‘prediction units’ (PUs), and ‘transform units’ (TUs). When separate coding trees are used for a given area, the above-mentioned CBs, as well as ‘prediction blocks’ (PBs), and ‘transform blocks’ (TBs) are used.

[0007] Notwithstanding the above distinction between ‘units’ and ‘blocks’, the term ‘block’ may be used as a general term for areas or regions of a frame for which operations are applied to all colour channels.

[0008] For each CU a prediction unit (PU) of the contents (sample values) of the corresponding area of frame data is generated (a ‘prediction unit’). Further, a representation of the difference (or ‘residual’ in the spatial domain) between the prediction and the contents of the area as seen at input to the encoder is formed. The difference in each colour channel may be transformed and coded as a sequence of residual coefficients, forming one or more TUs for a given CU. The applied transform may be a Discrete Cosine Transform (DCT) or other transform, applied to each block of residual

values. This transform is applied separably, i.e. that is the two-dimensional transform is performed in two passes. The block is firstly transformed by applying a one-dimensional transform to each row of samples in the block. Then, the partial result is transformed by applying a one-dimensional transform to each column of the partial result to produce a final block of transform coefficients that substantially decorrelates the residual samples. Transforms of various sizes are supported by the VVC standard, including transforms of rectangular-shaped blocks, with each side dimension being a power of two. Transform coefficients are quantised for entropy encoding into a bitstream.

[0009] VVC features an intra-frame prediction and inter-frame prediction. Intra-frame prediction involves the use of previously processed samples in a frame being used to generate a prediction of a current block of samples in the frame. Inter-frame prediction involves generating a prediction of a current block of samples in a frame using a block of samples obtained from a previously decoded frame. The previously decoded frame is offset from the spatial location of the current block according to a motion vector, which often has filtering being applied. Intra-frame prediction blocks can be a uniform sample value (“DC intra prediction”), a plane having an offset and horizontal and vertical gradient (“planar intra prediction”), or a population of the block with neighbouring samples applied in a particular direction (“angular intra prediction”) or the result of a matrix multiplication using neighbouring samples and selected matrix coefficients. As neighbouring samples include samples from the previously processed block the feedback loop for intra-frame prediction is quite restrictive, and computational complexity needs to be kept below the level required to meet the highest supported resolution and frame rate.

SUMMARY

[0010] It is an object of the present invention to substantially overcome, or at least ameliorate, one or more disadvantages of existing arrangements.

[0011] One aspect of the present disclosure provides a method of decoding coding units of a coding tree for an image frame from a video bitstream, the method comprising: splitting a region of the coding tree into a plurality of coding blocks, each of the coding blocks including a prediction block; determining matrix intra prediction flags for the prediction block of each of the coding blocks, each matrix intra prediction flag indicating whether matrix intra prediction is used for the prediction block of one of the coding blocks, the determination based upon (i) an area of the region if the region meets a threshold, or (ii) a budget for the region if the area of the region does not meet the threshold; reading matrix coefficients from a memory for each prediction block determined to use matrix intra prediction according to the determined flag; and decoding the coding units using prediction blocks generated for each coding unit in the region using reference samples of each prediction block and the matrix coefficients.

[0012] In another aspect, the threshold is a size of greater than 512 luma samples.

[0013] In another aspect, the threshold is a size of greater than 64 luma samples.

[0014] In another aspect, the budget allows reading of 40 word reads of a 4×4 block for the region.

[0015] In another aspect, matrix intra prediction flags are decoded for the CU only if matrix intra prediction is used.

[0016] In another aspect, matrix intra prediction flags are decoded for the CU regardless of whether matrix intra prediction is used.

[0017] Another aspect of the present disclosure provides a method of decoding coding units of a coding tree for an image frame from a video bitstream, the method comprising: splitting a region of the coding tree into a plurality of coding blocks, each including a prediction block; determining matrix intra prediction flag for predictions block of the coding blocks based on a size of each coding block, each matrix intra prediction flag indicating whether matrix intra prediction is used for the prediction block of the corresponding coding block; reading matrix coefficients from a memory for each prediction block determined to use matrix intra prediction according to the determined flag; and decoding coding units from prediction blocks for each coding unit in the region generated using reference samples of each prediction block and the matrix coefficients.

[0018] In another aspect, matrix intra prediction flags are decoded if the size of the coding unit is not 4×4 .

[0019] In another aspect, matrix intra prediction flags are decoded if the size of the coding unit is not one of 4×4 , 8×4 or 4×8 .

[0020] In another aspect, matrix intra prediction flags are decoded if the size of the coding unit is not one of 4×4 , 8×4 , 4×8 or 8×8 .

[0021] In another aspect, the matrix intra prediction flags are decoded if the size of the coding unit is not one of 4×4 , 8×4 , 4×8 , 8×8 , 8×16 or 16×8 .

[0022] Another aspect of the present disclosure provides a method of generating a prediction block of a coding tree for an image frame from a video bitstream, the method comprising: determining a prediction mode for the coding unit by decoding a matrix intra prediction mode flag from the video bitstream; where a prediction mode indicates the use of a matrix intra prediction mode, decoding a truncated binary codeword to determine a matrix intra prediction mode; and generating the prediction block by applying a matrix multiplication to reference samples neighbouring the prediction block and a matrix selected according to the decoded matrix intra prediction mode.

[0023] Another aspect of the present disclosure provides a non-transitory computer-readable medium having a computer program stored thereon to implement a method of method of decoding coding units of a coding tree for an image frame from a video bitstream, the method comprising: splitting a region of the coding tree into a plurality of coding blocks, each of the coding blocks including a prediction block; determining matrix intra prediction flags for the prediction block of each of the coding blocks, each matrix intra prediction flag indicating whether matrix intra prediction is used for the prediction block of one of the coding blocks, the determination based upon (i) an area of the region if the region meets a threshold, or (ii) a budget for the region if the area of the region does not meet the threshold; reading matrix coefficients from a memory for each prediction block determined to use matrix intra prediction according to the determined flag; and decoding the coding units using prediction blocks generated for each coding unit in the region using reference samples of each prediction block and the matrix coefficients.

[0024] Another aspect of the present disclosure provides a video decoder, configured to receive coding units of a coding tree for an image frame from a video bitstream; split a region of the coding tree into a plurality of coding blocks, each of the coding blocks including a prediction block; determine matrix intra prediction flags for the prediction block of each of the coding blocks, each matrix intra prediction flag indicating whether matrix intra prediction is used for the prediction block of one of the coding blocks, the determination based upon (i) an area of the region if the region meets a threshold, or (ii) a budget for the region if the area of the region does not meet the threshold; read matrix coefficients from a memory for each prediction block determined to use matrix intra prediction according to the determined flag; and decode the coding units using prediction blocks generated for each coding unit in the region using reference samples of each prediction block and the matrix coefficients.

[0025] Another aspect of the present disclosure provides a system, comprising: a memory; and a processor, wherein the processor is configured to execute code stored on the memory for implementing a method of decoding coding units of a coding tree for an image frame from a video bitstream, the method comprising: splitting a region of the coding tree into a plurality of coding blocks, each of the coding blocks including a prediction block; determining matrix intra prediction flags for the prediction block of each of the coding blocks, each matrix intra prediction flag indicating whether matrix intra prediction is used for the prediction block of one of the coding blocks, the determination based upon (i) an area of the region if the region meets a threshold, or (ii) a budget for the region if the area of the region does not meet the threshold; reading matrix coefficients from a memory for each prediction block determined to use matrix intra prediction according to the determined flag; and decoding the coding units using prediction blocks generated for each coding unit in the region using reference samples of each prediction block and the matrix

coefficients.

[0026] Other aspects are also disclosed.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] At least one embodiment of the present invention will now be described with reference to the following drawings and and appendices, in which:

[0028] FIG. 1 is a schematic block diagram showing a video encoding and decoding system;

[0029] FIGS. 2A and 2B form a schematic block diagram of a general purpose computer system upon which one or both of the video encoding and decoding system of FIG. 1 may be practiced;

[0030] FIG. 3 is a schematic block diagram showing functional modules of a video encoder;

[0031] FIG. 4 is a schematic block diagram showing functional modules of a video decoder;

[0032] FIG. 5 is a schematic block diagram showing the available divisions of a block into one or more blocks in the tree structure of versatile video coding;

[0033] FIG. 6 is a schematic illustration of a dataflow to achieve permitted divisions of a block into one or more blocks in a tree structure of versatile video coding;

[0034] FIGS. 7A and 7B show an example division of a coding tree unit (CTU) into a number of coding units (CUs);

[0035] FIG. 8 shows an example of operation of the matrix intra prediction module;

[0036] FIGS. 9A and 9B show an example CTU with regions within which memory access bandwidth for matrix intra prediction mode is applied;

[0037] FIG. 10 shows a coding tree corresponding to the example of FIG. 9;

[0038] FIG. 11 shows a method for encoding coding units, including coding units with use of matrix intra prediction, of an image frame into a video bitstream;

[0039] FIG. 12 shows a method for determining a budget for memory access for matrix intra prediction spanning multiple coding units of a coding tree unit as used in FIG. 11;

[0040] FIG. 13 shows a method for determining a coding unit for encoding a portion of an image frame into a video bitstream as used in FIG. 11;

[0041] FIG. 14 shows a method for encoding a coding unit of an image frame to a video bitstream as used in FIG. 11;

[0042] FIG. 15 shows a method for decoding coding trees of an image frame from a video bitstream;

[0043] FIG. 16 shows a method for decoding a coding unit of an image frame from a video bitstream as used in FIG. 15;

[0044] FIG. 17 shows an alternative method for determining a coding unit for encoding a portion of an image frame into a video bitstream as used in FIG. 11;

[0045] FIG. 18 shows an alternative method for encoding a coding unit of an image frame to a video bitstream as used in FIG. 11; and

[0046] FIG. 19 shows an alternative method for decoding a coding unit of an image frame from a video bitstream as used in FIG. 15.

DETAILED DESCRIPTION INCLUDING BEST MODE

[0047] Where reference is made in any one or more of the accompanying drawings to steps and/or features, which have the same reference numerals, those steps and/or features have for the purposes of this description the same function(s) or operation(s), unless the contrary intention appears.

[0048] As described above, computational complexity of intra-frame prediction is restrictive, particularly for matrix intra prediction (MIP). While MIP can provide an effective solution in terms of minimising error, computational complexity of applying MIP particularly affects the block processing rate in the worst case, for example a frame composed exclusively of 4×4 blocks. The

block processing rate needs to be sufficient to support the resolution and frame rate of the targeted application. Considering a luma channel only, an “8K” resolution frame (7680×4320) at 120 frames per second requires processing 248.8×10^{sup.6} 4×4 blocks per second. Even where the worst case is not realised throughout an entire frame or video sequence, localised regions reaching the worst case need to be processed without delaying delivery of a completely decoded frame for presentation on a display. One aspect of complexity relates to the memory bandwidth needed to fetch matrix coefficients selected according to a matrix intra prediction (MIP) mode, which may vary from block to block without constraint.

[0049] FIG. 1 is a schematic block diagram showing functional modules of a video encoding and decoding system **100**. The system **100** can utilise constraints on application of MIP mode to establish a worst case memory bandwidth for selecting or reading matrix coefficients in order to allow practical implementation and/or commensurate with the coding advantage achieved by the MIP mode.

[0050] The system **100** includes a source device **110** and a destination device **130**. A communication channel **120** is used to communicate encoded video information from the source device **110** to the destination device **130**. In some arrangements, the source device **110** and destination device **130** may either or both comprise respective mobile telephone handsets or “smartphones”, in which case the communication channel **120** is a wireless channel. In other arrangements, the source device **110** and destination device **130** may comprise video conferencing equipment, in which case the communication channel **120** is typically a wired channel, such as an internet connection. Moreover, the source device **110** and the destination device **130** may comprise any of a wide range of devices, including devices supporting over-the-air television broadcasts, cable television applications, internet video applications (including streaming) and applications where encoded video data is captured on some computer-readable storage medium, such as hard disk drives in a file server.

[0051] As shown in FIG. 1, the source device **110** includes a video source **112**, a video encoder **114** and a transmitter **116**. The video source **112** typically comprises a source of captured video frame data (shown as **113**), such as an image capture sensor, a previously captured video sequence stored on a non-transitory recording medium, or a video feed from a remote image capture sensor. The video source **112** may also be an output of a computer graphics card, for example displaying the video output of an operating system and various applications executing upon a computing device, for example a tablet computer. Examples of source devices **110** that may include an image capture sensor as the video source **112** include smart-phones, video camcorders, professional video cameras, and network video cameras.

[0052] The video encoder **114** converts (or ‘encodes’) the captured frame data (indicated by an arrow **113**) from the video source **112** into a bitstream (indicated by an arrow **115**) as described further with reference to FIG. 3. The bitstream **115** is transmitted by the transmitter **116** over the communication channel **120** as encoded video data (or “encoded video information”). It is also possible for the bitstream **115** to be stored in a non-transitory storage device **122**, such as a “Flash” memory or a hard disk drive, until later being transmitted over the communication channel **120**, or in-lieu of transmission over the communication channel **120**. For example, encoded video data may be served upon demand to customers over a wide area network (WAN) for a video streaming application.

[0053] The destination device **130** includes a receiver **132**, a video decoder **134** and a display device **136**. The receiver **132** receives encoded video data from the communication channel **120** and passes received video data to the video decoder **134** as a bitstream (indicated by an arrow **133**). The video decoder **134** then outputs decoded frame data (indicated by an arrow **135**) to the display device **136**. The decoded frame data **135** has the same chroma format as the frame data **113**. Examples of the display device **136** include a cathode ray tube, a liquid crystal display, such as in smart-phones, tablet computers, computer monitors or in stand-alone television sets. It is also

possible for the functionality of each of the source device **110** and the destination device **130** to be embodied in a single device, examples of which include mobile telephone handsets and tablet computers.

[0054] Notwithstanding the example devices mentioned above, each of the source device **110** and destination device **130** may be configured within a general purpose computing system, typically through a combination of hardware and software components. FIG. 2A illustrates such a computer system **200**, which includes: a computer module **201**; input devices such as a keyboard **202**, a mouse pointer device **203**, a scanner **226**, a camera **227**, which may be configured as the video source **112**, and a microphone **280**; and output devices including a printer **215**, a display device **214**, which may be configured as the display device **136**, and loudspeakers **217**. An external Modulator-Demodulator (Modem) transceiver device **216** may be used by the computer module **201** for communicating to and from a communications network **220** via a connection **221**. The communications network **220**, which may represent the communication channel **120**, may be a (WAN), such as the Internet, a cellular telecommunications network, or a private WAN. Where the connection **221** is a telephone line, the modem **216** may be a traditional “dial-up” modem. Alternatively, where the connection **221** is a high capacity (e.g., cable or optical) connection, the modem **216** may be a broadband modem. A wireless modem may also be used for wireless connection to the communications network **220**. The transceiver device **216** may provide the functionality of the transmitter **116** and the receiver **132** and the communication channel **120** may be embodied in the connection **221**.

[0055] The computer module **201** typically includes at least one processor unit **205**, and a memory unit **206**. For example, the memory unit **206** may have semiconductor random access memory (RAM) and semiconductor read only memory (ROM). The computer module **201** also includes a number of input/output (I/O) interfaces including: an audio-video interface **207** that couples to the video display **214**, loudspeakers **217** and microphone **280**; an I/O interface **213** that couples to the keyboard **202**, mouse **203**, scanner **226**, camera **227** and optionally a joystick or other human interface device (not illustrated); and an interface **208** for the external modem **216** and printer **215**. The signal from the audio-video interface **207** to the computer monitor **214** is generally the output of a computer graphics card. In some implementations, the modem **216** may be incorporated within the computer module **201**, for example within the interface **208**. The computer module **201** also has a local network interface **211**, which permits coupling of the computer system **200** via a connection **223** to a local-area communications network **222**, known as a Local Area Network (LAN). As illustrated in FIG. 2A, the local communications network **222** may also couple to the wide network **220** via a connection **224**, which would typically include a so-called “firewall” device or device of similar functionality. The local network interface **211** may comprise an Ethernet™ circuit card, a Bluetooth™ wireless arrangement or an IEEE 802.11 wireless arrangement; however, numerous other types of interfaces may be practiced for the interface **211**. The local network interface **211** may also provide the functionality of the transmitter **116** and the receiver **132** and communication channel **120** may also be embodied in the local communications network **222**.

[0056] The I/O interfaces **208** and **213** may afford either or both of serial and parallel connectivity, the former typically being implemented according to the Universal Serial Bus (USB) standards and having corresponding USB connectors (not illustrated). Storage devices **209** are provided and typically include a hard disk drive (HDD) **210**. Other storage devices such as a floppy disk drive and a magnetic tape drive (not illustrated) may also be used. An optical disk drive **212** is typically provided to act as a non-volatile source of data. Portable memory devices, such optical disks (e.g. CD-ROM, DVD, Blu ray Disc™), USB-RAM, portable, external hard drives, and floppy disks, for example, may be used as appropriate sources of data to the computer system **200**. Typically, any of the HDD **210**, optical drive **212**, networks **220** and **222** may also be configured to operate as the video source **112**, or as a destination for decoded video data to be stored for reproduction via the display **214**. The source device **110** and the destination device **130** of the system **100** may be

embodied in the computer system **200**.

[0057] The components **205** to **213** of the computer module **201** typically communicate via an interconnected bus **204** and in a manner that results in a conventional mode of operation of the computer system **200** known to those in the relevant art. For example, the processor **205** is coupled to the system bus **204** using a connection **218**. Likewise, the memory **206** and optical disk drive **212** are coupled to the system bus **204** by connections **219**. Examples of computers on which the described arrangements can be practised include IBM-PC's and compatibles, Sun SPARCstations, Apple Mac™ or alike computer systems.

[0058] Where appropriate or desired, the video encoder **114** and the video decoder **134**, as well as methods described below, may be implemented using the computer system **200**. In particular, the video encoder **114**, the video decoder **134** and methods to be described, may be implemented as one or more software application programs **233** executable within the computer system **200**. In particular, the video encoder **114**, the video decoder **134** and the steps of the described methods are effected by instructions **231** (see FIG. 2B) in the software **233** that are carried out within the computer system **200**. The software instructions **231** may be formed as one or more code modules, each for performing one or more particular tasks. The software may also be divided into two separate parts, in which a first part and the corresponding code modules performs the described methods and a second part and the corresponding code modules manage a user interface between the first part and the user.

[0059] The software may be stored in a computer readable medium, including the storage devices described below, for example. The software is loaded into the computer system **200** from the computer readable medium, and then executed by the computer system **200**. A computer readable medium having such software or computer program recorded on the computer readable medium is a computer program product. The use of the computer program product in the computer system **200** preferably effects an advantageous apparatus for implementing the video encoder **114**, the video decoder **134** and the described methods.

[0060] The software **233** is typically stored in the HDD **210** or the memory **206**. The software is loaded into the computer system **200** from a computer readable medium, and executed by the computer system **200**. Thus, for example, the software **233** may be stored on an optically readable disk storage medium (e.g., CD-ROM) **225** that is read by the optical disk drive **212**.

[0061] In some instances, the application programs **233** may be supplied to the user encoded on one or more CD-ROMs **225** and read via the corresponding drive **212**, or alternatively may be read by the user from the networks **220** or **222**. Still further, the software can also be loaded into the computer system **200** from other computer readable media. Computer readable storage media refers to any non-transitory tangible storage medium that provides recorded instructions and/or data to the computer system **200** for execution and/or processing. Examples of such storage media include floppy disks, magnetic tape, CD-ROM, DVD, Blu-ray Disc™, a hard disk drive, a ROM or integrated circuit, USB memory, a magneto-optical disk, or a computer readable card such as a PCMCIA card and the like, whether or not such devices are internal or external of the computer module **201**. Examples of transitory or non-tangible computer readable transmission media that may also participate in the provision of the software, application programs, instructions and/or video data or encoded video data to the computer module **401** include radio or infra-red transmission channels, as well as a network connection to another computer or networked device, and the Internet or Intranets including e-mail transmissions and information recorded on Websites and the like.

[0062] The second part of the application program **233** and the corresponding code modules mentioned above may be executed to implement one or more graphical user interfaces (GUIs) to be rendered or otherwise represented upon the display **214**. Through manipulation of typically the keyboard **202** and the mouse **203**, a user of the computer system **200** and the application may manipulate the interface in a functionally adaptable manner to provide controlling commands

and/or input to the applications associated with the GUI(s). Other forms of functionally adaptable user interfaces may also be implemented, such as an audio interface utilizing speech prompts output via the loudspeakers **217** and user voice commands input via the microphone **280**.

[0063] FIG. **2B** is a detailed schematic block diagram of the processor **205** and a “memory” **234**. The memory **234** represents a logical aggregation of all the memory modules (including the HDD **209** and semiconductor memory **206**) that can be accessed by the computer module **201** in FIG. **2A**.

[0064] When the computer module **201** is initially powered up, a power-on self-test (POST) program **250** executes. The POST program **250** is typically stored in a ROM **249** of the semiconductor memory **206** of FIG. **2A**. A hardware device such as the ROM **249** storing software is sometimes referred to as firmware. The POST program **250** examines hardware within the computer module **201** to ensure proper functioning and typically checks the processor **205**, the memory **234** (**209**, **206**), and a basic input-output systems software (BIOS) module **251**, also typically stored in the ROM **249**, for correct operation. Once the POST program **250** has run successfully, the BIOS **251** activates the hard disk drive **210** of FIG. **2A**. Activation of the hard disk drive **210** causes a bootstrap loader program **252** that is resident on the hard disk drive **210** to execute via the processor **205**. This loads an operating system **253** into the RAM memory **206**, upon which the operating system **253** commences operation. The operating system **253** is a system level application, executable by the processor **205**, to fulfil various high level functions, including processor management, memory management, device management, storage management, software application interface, and generic user interface.

[0065] The operating system **253** manages the memory **234** (**209**, **206**) to ensure that each process or application running on the computer module **201** has sufficient memory in which to execute without colliding with memory allocated to another process. Furthermore, the different types of memory available in the computer system **200** of FIG. **2A** must be used properly so that each process can run effectively. Accordingly, the aggregated memory **234** is not intended to illustrate how particular segments of memory are allocated (unless otherwise stated), but rather to provide a general view of the memory accessible by the computer system **200** and how such is used.

[0066] As shown in FIG. **2B**, the processor **205** includes a number of functional modules including a control unit **239**, an arithmetic logic unit (ALU) **240**, and a local or internal memory **248**, sometimes called a cache memory. The cache memory **248** typically includes a number of storage registers **244-246** in a register section. One or more internal busses **241** functionally interconnect these functional modules. The processor **205** typically also has one or more interfaces **242** for communicating with external devices via the system bus **204**, using a connection **218**. The memory **234** is coupled to the bus **204** using a connection **219**.

[0067] The application program **233** includes a sequence of instructions **231** that may include conditional branch and loop instructions. The program **233** may also include data **232** which is used in execution of the program **233**. The instructions **231** and the data **232** are stored in memory locations **228**, **229**, **230** and **235**, **236**, **237**, respectively. Depending upon the relative size of the instructions **231** and the memory locations **228-230**, a particular instruction may be stored in a single memory location as depicted by the instruction shown in the memory location **230**. Alternately, an instruction may be segmented into a number of parts each of which is stored in a separate memory location, as depicted by the instruction segments shown in the memory locations **228** and **229**.

[0068] In general, the processor **205** is given a set of instructions which are executed therein. The processor **205** waits for a subsequent input, to which the processor **205** reacts to by executing another set of instructions. Each input may be provided from one or more of a number of sources, including data generated by one or more of the input devices **202**, **203**, data received from an external source across one of the networks **220**, **202**, data retrieved from one of the storage devices **206**, **209** or data retrieved from a storage medium **225** inserted into the corresponding reader **212**,

all depicted in FIG. 2A. The execution of a set of the instructions may in some cases result in output of data. Execution may also involve storing data or variables to the memory **234**.

[0069] The video encoder **114**, the video decoder **134** and the described methods may use input variables **254**, which are stored in the memory **234** in corresponding memory locations **255**, **256**, **257**. The video encoder **114**, the video decoder **134** and the described methods produce output variables **261**, which are stored in the memory **234** in corresponding memory locations **262**, **263**, **264**. Intermediate variables **258** may be stored in memory locations **259**, **260**, **266** and **267**.

[0070] Referring to the processor **205** of FIG. 2B, the registers **244**, **245**, **246**, the arithmetic logic unit (ALU) **240**, and the control unit **239** work together to perform sequences of micro-operations needed to perform “fetch, decode, and execute” cycles for every instruction in the instruction set making up the program **233**. Each fetch, decode, and execute cycle comprises: [0071] a fetch operation, which fetches or reads an instruction **231** from a memory location **228**, **229**, **230**; [0072] a decode operation in which the control unit **239** determines which instruction has been fetched; and [0073] an execute operation in which the control unit **239** and/or the ALU **240** execute the instruction.

[0074] Thereafter, a further fetch, decode, and execute cycle for the next instruction may be executed. Similarly, a store cycle may be performed by which the control unit **239** stores or writes a value to a memory location **232**.

[0075] Each step or sub-process in the method of FIGS. **11** to **19**, to be described, is associated with one or more segments of the program **233** and is typically performed by the register section **244**, **245**, **247**, the ALU **240**, and the control unit **239** in the processor **205** working together to perform the fetch, decode, and execute cycles for every instruction in the instruction set for the noted segments of the program **233**.

[0076] FIG. **3** is a schematic block diagram showing functional modules of the video encoder **114**. FIG. **4** is a schematic block diagram showing functional modules of the video decoder **134**.

Generally, data passes between functional modules within the video encoder **114** and the video decoder **134** in groups of samples or coefficients, such as divisions of blocks into sub-blocks of a fixed size, or as arrays. The video encoder **114** and video decoder **134** may be implemented using a general-purpose computer system **200**, as shown in FIGS. **2A** and **2B**, where the various functional modules may be implemented by dedicated hardware within the computer system **200**, by software executable within the computer system **200** such as one or more software code modules of the software application program **233** resident on the hard disk drive **205** and being controlled in its execution by the processor **205**. Alternatively, the video encoder **114** and video decoder **134** may be implemented by a combination of dedicated hardware and software executable within the computer system **200**. The video encoder **114**, the video decoder **134** and the described methods may alternatively be implemented in dedicated hardware, such as one or more integrated circuits performing the functions or sub functions of the described methods. Such dedicated hardware may include graphic processing units (GPUs), digital signal processors (DSPs), application-specific standard products (ASSPs), application-specific integrated circuits (ASICs), field programmable gate arrays (FPGAs) or one or more microprocessors and associated memories. In particular, the video encoder **114** comprises modules **310-392** and the video decoder **134** comprises modules **420-496** which may each be implemented as one or more software code modules of the software application program **233**.

[0077] Although the video encoder **114** of FIG. **3** is an example of a versatile video coding (VVC) video encoding pipeline, other video codecs may also be used to perform the processing stages described herein. The video encoder **114** receives captured frame data **113**, such as a series of frames, each frame including one or more colour channels. The frame data **113** may be in any chroma format, for example 4:0:0, 4:2:0, 4:2:2, or 4:4:4 chroma format. A block partitioner **310** firstly divides the frame data **113** into CTUs, generally square in shape and configured such that a particular size for the CTUs is used. The size of the CTUs may be 64×64, 128×128, or 256×256

luma samples for example. The block partitioner **310** further divides each CTU into one or more CBs according to a luma coding tree and a chroma coding tree. The CBs have a variety of sizes, and may include both square and non-square aspect ratios. Operation of the block partitioner **310** is further described with reference to FIGS. **11-19**. However, in the VVC standard, CBs, CUs, PUs, and TUs always have side lengths that are powers of two. Thus, a current CB, represented as **312**, is output from the block partitioner **310**, progressing in accordance with an iteration over the one or more blocks of the CTU, in accordance with the luma coding tree and the chroma coding tree of the CTU. Options for partitioning CTUs into CBs are further described below with reference to FIGS. **5** and **6**. Although operation is generally described on a CTU-by-CTU basis, the video encoder **114** and the video decoder **134** can operate on a smaller-sized region to reduce memory consumption. For example, each CTU can be divided into smaller regions, known as ‘virtual pipeline data units’ (VPDUs) of size 64×64. The VPDUs form a granularity of data that is more amenable to pipeline processing in hardware architectures where the reduction in memory footprint reduces silicon area and hence cost, compared to operating on full CTUs.

[0078] The CTUs resulting from the first division of the frame data **113** may be scanned in raster scan order and may be grouped into one or more ‘slices’. A slice may be an ‘intra’ (or ‘I’) slice. An intra slice (I slice) indicates that every CU in the slice is intra predicted. Alternatively, a slice may be uni- or bi-predicted (‘P’ or ‘B’ slice, respectively), indicating additional availability of uni- and bi-prediction in the slice, respectively.

[0079] For each CTU, the video encoder **114** operates in two stages. In the first stage (referred to as a ‘search’ stage), the block partitioner **310** tests various potential configurations of a coding tree. Each potential configuration of a coding tree has associated ‘candidate’ CBs. The first stage involves testing various candidate CBs to select CBs providing relatively high compression efficiency with relatively low distortion. The testing generally involves a Lagrangian optimisation whereby a candidate CB is evaluated based on a weighted combination of the rate (coding cost) and the distortion (error with respect to the input frame data **113**). The ‘best’ candidate CBs (the CBs with the lowest evaluated rate/distortion) are selected for subsequent encoding into the bitstream **115**. Included in evaluation of candidate CBs is an option to use a CB for a given area or to further split the area according to various splitting options and code each of the smaller resulting areas with further CBs, or split the areas even further. As a consequence, both the CBs and the coding tree themselves are selected in the search stage.

[0080] The video encoder **114** produces a prediction block (PB), indicated by an arrow **320**, for each CB, for example the CB **312**. The PB **320** is a prediction of the contents of the associated CB **312**. A subtracter module **322** produces a difference, indicated as **324** (or ‘residual’, referring to the difference being in the spatial domain), between the PB **320** and the CB **312**. The difference **324** is a block-size difference between corresponding samples in the PB **320** and the CB **312**. The difference **324** is transformed, quantised and represented as a transform block (TB), indicated by an arrow **336**. The PB **320** and associated TB **336** are typically chosen from one of many possible candidate CBs, for example based on evaluated cost or distortion.

[0081] A candidate coding block (CB) is a CB resulting from one of the prediction modes available to the video encoder **114** for the associated PB and the resulting residual. The TB **336** is a quantised and transformed representation of the difference **324**. When combined with the predicted PB in the video decoder **114**, the TB **336** reduces the difference between decoded CBs and the original CB **312** at the expense of additional signalling in a bitstream.

[0082] Each candidate coding block (CB), that is prediction block (PB) in combination with a transform block (TB), thus has an associated coding cost (or ‘rate’) and an associated difference (or ‘distortion’). The rate is usually measured in bits. The distortion of the CB is typically estimated as a difference in sample values, such as a sum of absolute differences (SAD) or a sum of squared differences (SSD). The estimate resulting from each candidate PB may be determined by a mode selector **386** using the difference **324** to determine a prediction mode **387**. The prediction mode **387**

indicates the decision to use intra-frame prediction, inter-frame prediction, or matrix intra prediction (MIP) for the current CB. The prediction mode **387** is determined as a selected mode among possible modes including intra prediction (including matrix intra prediction, DC, planar, and angular intra prediction) or inter prediction, with an associated motion vector. The prediction mode **387** is typically selected by minimising a distortion metric that results from a Lagrangian optimisation of the distortion resulting from each candidate mode summed with the result of scaling the associated rate with a Lambda value. When matrix intra prediction is in use, a matrix intra prediction mode (represented by an arrow **388**) is also determined to indicate which one of several available matrix intra prediction modes is used for the current CB. The search to decide the usage and selection of MIP modes for blocks, particularly relatively small blocks, may be constrained to achieve a lower worst case memory bandwidth for fetching matrix coefficients compared to an unconstrained search, as described with reference to FIGS. **11** to **14** and, in an alternative implementation, FIGS. **17** and **18**. Estimation of the coding costs associated with each candidate prediction mode and corresponding residual coding can be performed at significantly lower cost than entropy coding of the residual. Accordingly, a number of candidate modes can be evaluated to determine an optimum mode in a rate-distortion sense.

[0083] Determining an optimum mode in terms of rate-distortion is typically achieved using a variation of Lagrangian optimisation. Selection of the matrix intra prediction mode **388** typically involves determining a coding cost for the residual data resulting from application of a particular matrix intra prediction mode. The coding cost may be approximated by using a ‘sum of absolute transformed differences’ (SATD) whereby a relatively simple transform, such as a Hadamard transform, is used to obtain an estimated transformed residual cost. In some implementations using relatively simple transforms, the costs resulting from the simplified estimation method are monotonically related to the actual costs that would otherwise be determined from a full evaluation. In implementations with monotonically related estimated costs, the simplified estimation method may be used to make the same decision (i.e. intra prediction mode) with a reduction in complexity in the video encoder **114**. To allow for possible non-monotonicity in the relationship between estimated and actual costs, the simplified estimation method may be used to generate a list of best candidates. The non-monotonicity may result from further mode decisions available for the coding of residual data, for example. The list of best candidates may be of an arbitrary number. A more complete search may be performed using the best candidates to establish optimal mode choices for coding the residual data for each of the candidates, allowing a final selection of the intra prediction mode along with other mode decisions.

[0084] The other mode decisions include an ability to skip a forward transform, known as ‘transform skip’. Skipping the transforms is suited to residual data that lacks adequate correlation for reduced coding cost via expression as transform basis functions. Certain types of content, such as relatively simple computer generated graphics may exhibit similar behaviour. For a ‘skipped transform’, residual coefficients are still coded even though the transform itself is not performed.

[0085] Lagrangian or similar optimisation processing can be employed to both select an optimal partitioning of a CTU into CBs (by the block partitioner **310**) as well as the selection of a best prediction mode from a plurality of possibilities. Through application of a Lagrangian optimisation process of the candidate modes in the mode selector module **386**, the intra prediction mode with the lowest cost measurement is selected as the ‘best’ mode. The lowest cost mode is the selected intra prediction mode **388** and is also encoded in the bitstream **115** by an entropy encoder **338**. The selection of the intra prediction mode **388** by operation of the mode selector module **386** extends to operation of the block partitioner **310**. For example, candidates for selection of the intra prediction mode **388** may include modes applicable to a given block and additionally modes applicable to multiple smaller blocks that collectively are collocated with the given block. In cases including modes applicable to a given block and smaller collocated blocks, the process of selection of candidates implicitly is also a process of determining the best hierarchical decomposition of the

CTU into CBs.

[0086] In the second stage of operation of the video encoder **114** (referred to as a ‘coding’ stage), an iteration over the selected luma coding tree and the selected chroma coding tree, and hence each selected CB, is performed in the video encoder **114**. In the iteration, the CBs are encoded into the bitstream **115**, as described further herein.

[0087] The entropy encoder **338** supports both variable-length coding of syntax elements and arithmetic coding of syntax elements. Arithmetic coding is supported using a context-adaptive binary arithmetic coding process. Arithmetically coded syntax elements consist of sequences of one or more ‘bins’. Bins, like bits, have a value of ‘0’ or ‘1’. However, bins are not encoded in the bitstream **115** as discrete bits. Bins have an associated predicted (or ‘likely’ or ‘most probable’) value and an associated probability, known as a ‘context’. When the actual bin to be coded matches the predicted value, a ‘most probable symbol’ (MPS) is coded. Coding a most probable symbol is relatively inexpensive in terms of consumed bits in the bitstream **115**, including costs that amount to less than one discrete bit. When the actual bin to be coded mismatches the likely value, a ‘least probable symbol’ (LPS) is coded. Coding a least probable symbol has a relatively high cost in terms of consumed bits. The bin coding techniques enable efficient coding of bins where the probability of a ‘0’ versus a ‘1’ is skewed. For a syntax element with two possible values (that is, a ‘flag’), a single bin is adequate. For syntax elements with many possible values, a sequence of bins is needed.

[0088] The presence of later bins in the sequence may be determined based on the value of earlier bins in the sequence. Additionally, each bin may be associated with more than one context. The selection of a particular context can be dependent on earlier bins in the syntax element, the bin values of neighbouring syntax elements (i.e. those from neighbouring blocks) and the like. Each time a context-coded bin is encoded, the context that was selected for that bin (if any) is updated in a manner reflective of the new bin value. As such, the binary arithmetic coding scheme is said to be adaptive.

[0089] Also supported by the video encoder **114** are bins that lack a context (‘bypass bins’). Bypass bins are coded assuming an equiprobable distribution between a ‘0’ and a ‘1’. Thus, each bin occupies one bit in the bitstream **115**. The absence of a context saves memory and reduces complexity, and thus bypass bins are used where the distribution of values for the particular bin is not skewed. One example of an entropy coder employing context and adaption is known in the art as CABAC (context adaptive binary arithmetic coder) and many variants of this coder have been employed in video coding.

[0090] The entropy encoder **338** encodes the prediction mode **387** and, if in use for the current CB the matrix intra prediction mode **388**, using a combination of context-coded and bypass-coded bins. Blocks of size 4×4 have 35 possible matrix intra prediction modes, otherwise blocks not exceeding 8×8 in size (i.e. 4×8 , 8×4 , and 8×8) have 19 possible matrix intra prediction modes. For other block sizes there are 11 possible matrix intra prediction modes. Typically, a list of ‘most probable matrix modes’ (MPMs) is generated in the video encoder **114**. The list of most probable modes is typically of a fixed length, such as three modes. The list of most probable modes may include modes encountered in earlier blocks, adjacent to the current block. For example, were the blocks above or left of the current block to use MIP mode, the corresponding modes are present as MPMs for the current block. Were the blocks above or left of the current block to use angular intra prediction, the MPM list for the current block may be populated with MIP modes derived via a look-up table mapping angular intra prediction modes to MIP modes. Additionally, the MPM list of subsequent CUs predicted using regular intra prediction (DC, planar, or angular) can include candidate intra prediction modes derived from the CUs coded using MIP mode, with a mapping table from MIP mode to candidate regular intra prediction mode. A context-coded bin encodes a flag indicating if the intra prediction mode is one of the most probable modes. If the intra prediction mode **388** is one of the most probable modes, further signalling, using bypass-coded bins, is encoded. The encoded

further signalling is indicative of which most probable mode corresponds with the matrix intra prediction mode **388**, for example using a truncated unary bin string. Otherwise, the intra prediction mode **388** is encoded as a ‘remaining mode’. Encoding as a remaining mode uses an alternative syntax, such as a fixed-length code, also coded using bypass-coded bins, to express intra prediction modes other than those present in the most probable mode list.

[0091] Some arrangements can avoid the complexity of MPM list construction both for the current CU (coded using MIP mode) and subsequent CUs that may be coded using regular intra prediction mode and may include candidate intra prediction modes derived from any MIP-mode coded neighbour blocks. When MPM list construction is omitted, binarisation of the MIP mode is performed using a truncated binary code to represent the MIP mode. The truncated binary code results in a relatively even coding cost for each MIP mode, whereas the MPM list has low coding cost for each MIP added to the MPM list. Statistics obtained from MIP mode selection do not show a strong bias towards selecting a MIP mode contained on the MPM list compared to MIP modes not contained on the MPM list, indicating that omitting generation of MPM lists does not reduce compression efficiency. For 4×4 blocks, the 35 possible MIP modes can be encoded using a 5- or 6-bit code, with 5 bits used for MIP modes 0-28 and 6 bits used for MIP modes 29-34. For 4×8, 8×4, and 8×8 blocks, the 19 possible MIP modes may be encoded using a 4- or 5-bit code, with 4 bits used for MIP modes 0-12 and 5 bits used for MIP modes 13-18. For other sized blocks, the 11 possible MIP modes may be encoded using a 3- or 4-bit code, with 3 bits used for MIP modes 0-4 and 4 bits used for MIP modes 5-10.

[0092] A multiplexer module **384** outputs the PB **320** according to the determined best prediction mode **387**, selecting from the tested prediction mode of each candidate CB. The candidate prediction modes need not include every conceivable prediction mode supported by the video encoder **114**.

[0093] In inter-frame prediction a prediction for a block is produced using samples from one or two frames preceding the current frame in an order of coding frames in the bitstream. Moreover, for inter-frame prediction, a single coding tree is typically used for both the luma channel and the chroma channels. The order of coding frames in the bitstream may differ from the order of the frames when captured or displayed. When one frame is used for prediction, the block is said to be ‘uni-predicted’ and has one associated motion vector. When two frames are used for prediction, the block is said to be ‘bi-predicted’ and has two associated motion vectors. For a P slice, each CU may be intra predicted or uni-predicted. For a B slice, each CU may be intra predicted, uni-predicted, or bi-predicted. Frames are typically coded using a ‘group of pictures’ structure, enabling a temporal hierarchy of frames. A temporal hierarchy of frames allows a frame to reference a preceding and a subsequent picture in the order of displaying the frames. The images are coded in the order necessary to ensure the dependencies for decoding each frame are met.

[0094] The samples are selected according to a motion vector and reference picture index. The motion vector and reference picture index applies to all colour channels and thus inter prediction is described primarily in terms of operation upon PUs rather than PBs. Within each category (that is, intra- and inter-frame prediction), different techniques may be applied to generate the PU. For example, intra prediction may use values from adjacent rows and columns of previously reconstructed samples, in combination with a direction to generate a PU according to a prescribed filtering and generation process. Alternatively, the PU may be described using a small number of parameters. Inter prediction methods may vary in the number of motion parameters and their precision. Motion parameters typically comprise a reference frame index, indicating which reference frame(s) from lists of reference frames are to be used plus a spatial translation for each of the reference frames, but may include more frames, special frames, or complex affine parameters such as scaling and rotation. In addition, a pre-determined motion refinement process may be applied to generate dense motion estimates based on referenced sample blocks.

[0095] Having determined and selected the PB **320**, and subtracted the PB **320** from the original

sample block at the subtractor **322**, a residual with lowest coding cost, represented as **324**, is obtained and subjected to lossy compression. The lossy compression process comprises the steps of transformation, quantisation and entropy coding. A forward primary transform module **326** applies a forward transform to the difference **324**, converting the difference **324** from the spatial domain to the frequency domain, and producing primary transform coefficients represented by an arrow **328**. The primary transform coefficients **328** are passed to a forward secondary transform module **330** to produce transform coefficients represented by an arrow **332** by performing a non-separable secondary transform (NSST) operation. The forward primary transform is typically separable, transforming a set of rows and then a set of columns of each block. The forward primary transform module **326** typically uses a type-II discrete cosine transform (DCT-2), although a type-VII discrete sine transform (DST-7) and a type-VIII discrete cosine transform (DCT-8) may also be available, for example horizontally for block widths not exceeding 16 samples and vertically for block heights not exceeding 16 samples. The transformation of each set of rows and columns is performed by applying one-dimensional transforms firstly to each row of a block to produce an intermediate result and then to each column of the intermediate result to produce a final result. The forward secondary transform of the module **330** is generally a non-separable transform, which is only applied for the residual of intra-predicted CUs and may nonetheless also be bypassed. The forward secondary transform operates either on 16 samples (arranged as the upper-left 4×4 sub-block of the primary transform coefficients **328**) or 64 samples (arranged as the upper-left 8×8 coefficients, arranged as four 4×4 sub-blocks of the primary transform coefficients **328**).

[0096] The transform coefficients **332** are passed to a quantiser module **334**. At the module **334**, quantisation in accordance with a ‘quantisation parameter’ is performed to produce residual coefficients, represented by the arrow **336**. The quantisation parameter is constant for a given TB and thus results in a uniform scaling for the production of residual coefficients for a TB. A non-uniform scaling is also possible by application of a ‘quantisation matrix’, whereby the scaling factor applied for each residual coefficient is derived from a combination of the quantisation parameter and the corresponding entry in a scaling matrix, typically having a size equal to that of the TB. The scaling matrix can have a size that is smaller than the size of the TB, and when applied to the TB a nearest neighbour approach is used to provide scaling values for each residual coefficient from a scaling matrix smaller in size than the TB size. The residual coefficients **336** are supplied to the entropy encoder **338** for encoding in the bitstream **115**. Typically, the residual coefficients of each TB with at least one significant residual coefficient of the TU are scanned to produce an ordered list of values, according to a scan pattern. The scan pattern generally scans the TB as a sequence of 4×4 ‘sub-blocks’, providing a regular scanning operation at the granularity of 4×4 sets of residual coefficients, with the arrangement of sub-blocks dependent on the size of the TB. Additionally, the prediction mode **387**, the matrix intra prediction mode (if in use) **388**, and the corresponding block partitioning are also encoded in the bitstream **115**.

[0097] As described above, the video encoder **114** needs access to a frame representation corresponding to the frame representation seen in the video decoder **134**. Thus, the residual coefficients **336** are also inverse quantised by a dequantiser module **340** to produce inverse transform coefficients, represented by an arrow **342**. The inverse transform coefficients **342** are passed through an inverse secondary transform module **344** to produce intermediate inverse transform coefficients, represented by an arrow **346**. The intermediate inverse transform coefficients **346** are passed to an inverse primary transform module **348** to produce residual samples, represented by an arrow **350**, of the TU. The types of inverse transform performed by the inverse secondary transform module **344** correspond with the types of forward transform performed by the forward secondary transform module **330**. The types of inverse transform performed by the inverse primary transform module **348** correspond with the types of primary transform performed by the primary transform module **326**. A summation module **352** adds the residual samples **350** and the PU **320** to produce reconstructed samples (indicated by an arrow **354**) of the CU.

[0098] The reconstructed samples **354** are passed to a reference sample cache **356** and an in-loop filters module **368**. The reference sample cache **356**, typically implemented using static RAM on an ASIC (thus avoiding costly off-chip memory access) provides minimal sample storage needed to satisfy the dependencies for generating intra-frame PBs for subsequent CUs in the frame. The minimal dependencies typically include a ‘line buffer’ of samples along the bottom of a row of CTUs, for use by the next row of CTUs and column buffering the extent of which is set by the height of the CTU. The reference sample cache **356** supplies reference samples (represented by an arrow **358**) to a reference sample filter **360**. The sample filter **360** applies a smoothing operation to produce filtered reference samples (indicated by an arrow **362**). The filtered reference samples **362** are used by an intra-frame prediction module **364** to produce an intra-predicted block of samples, represented by an arrow **366**. For each candidate intra prediction mode the intra-frame prediction module **364** produces a block of samples, that is **366**. The block of samples **366** is generated by the module **364** using techniques such as DC, planar or angular intra prediction, but not matrix intra prediction.

[0099] If the mode selector **386** selects matrix intra prediction for the current CB, the matrix intra prediction mode **388** is used to select (read) matrix coefficients **363** from a coefficient memory **392**. The matrix coefficients **363** are passed to a matrix intra prediction module **390**. The matrix intra prediction module **390** performs a matrix multiplication using the matrix coefficients **363** and the reference samples **358** to produce a matrix intra predicted block **393**. The multiplexor **384** outputs the matrix intra prediction block **393** as the PB **320**. The coefficient memory **392** has limited bandwidth available for providing the matrix coefficients **393**. In particular, a different matrix intra prediction mode may be used for each consecutive block, establishing a worst case memory bandwidth requirement. The mode selector **386** is operable to select MIP mode for blocks under constraints that reduce the worst case memory bandwidth of the coefficient memory **392** as described in relation to operation of FIGS. **11** to **14**. Reducing the worst case memory bandwidth of the coefficient memory **392** reduces complexity, for example hardware area for the memory, without resulting in a proportionate degradation in coding efficiency of the video encoder **114**. The reduced complexity is achieved without a proportionate degradation in coding efficiency because the statistics of MIP mode selection in an unconstrained search do not usually trigger the constraints imposed upon the MIP mode selection in the mode selector **386**. Thus, worst case memory bandwidth is reduced without a commensurate loss in coding performance.

[0100] The in-loop filters module **368** applies several filtering stages to the reconstructed samples **354**. The filtering stages include a ‘deblocking filter’ (DBF) which applies smoothing aligned to the CU boundaries to reduce artefacts resulting from discontinuities. Another filtering stage present in the in-loop filters module **368** is an ‘adaptive loop filter’ (ALF), which applies a Wiener-based adaptive filter to further reduce distortion. A further available filtering stage in the in-loop filters module **368** is a ‘sample adaptive offset’ (SAO) filter. The SAO filter operates by firstly classifying reconstructed samples into one or multiple categories and, according to the allocated category, applying an offset at the sample level.

[0101] Filtered samples, represented by an arrow **370**, are output from the in-loop filters module **368**. The filtered samples **370** are stored in a frame buffer **372**. The frame buffer **372** typically has the capacity to store several (for example up to 16) pictures and thus is stored in the memory **206**. The frame buffer **372** is not typically stored using on-chip memory due to the large memory consumption required. As such, access to the frame buffer **372** is costly in terms of memory bandwidth. The frame buffer **372** provides reference frames (represented by an arrow **374**) to a motion estimation module **376** and a motion compensation module **380**.

[0102] The motion estimation module **376** estimates a number of ‘motion vectors’ (indicated as **378**), each being a Cartesian spatial offset from the location of the present CB, referencing a block in one of the reference frames in the frame buffer **372**. A filtered block of reference samples (represented as **382**) is produced for each motion vector. The filtered reference samples **382** form

further candidate modes available for potential selection by the mode selector **386**. Moreover, for a given CU, the PU **320** may be formed using one reference block ('uni-predicted') or may be formed using two reference blocks ('bi-predicted'). For the selected motion vector, the motion compensation module **380** produces the PB **320** in accordance with a filtering process supportive of sub-pixel accuracy in the motion vectors. As such, the motion estimation module **376** (which operates on many candidate motion vectors) may perform a simplified filtering process compared to that of the motion compensation module **380** (which operates on the selected candidate only) to achieve reduced computational complexity. When the video encoder **114** selects inter prediction for a CU the motion vector **378** is encoded into the bitstream **115**.

[0103] Although the video encoder **114** of FIG. 3 is described with reference to versatile video coding (VVC), other video coding standards or implementations may also employ the processing stages of modules **310-386**. The frame data **113** (and bitstream **115**) may also be read from (or written to) memory **206**, the hard disk drive **210**, a CD-ROM, a Blu-ray Disk™ or other computer readable storage medium. Additionally, the frame data **113** (and bitstream **115**) may be received from (or transmitted to) an external source, such as a server connected to the communications network **220** or a radio-frequency receiver.

[0104] The video decoder **134** is shown in FIG. 4. Although the video decoder **134** of FIG. 4 is an example of a versatile video coding (VVC) video decoding pipeline, other video codecs may also be used to perform the processing stages described herein. As shown in FIG. 4, the bitstream **133** is input to the video decoder **134**. The bitstream **133** may be read from memory **206**, the hard disk drive **210**, a CD-ROM, a Blu-ray Disk™ or other non-transitory computer readable storage medium. Alternatively, the bitstream **133** may be received from an external source such as a server connected to the communications network **220** or a radio-frequency receiver. The bitstream **133** contains encoded syntax elements representing the captured frame data to be decoded.

[0105] The bitstream **133** is input to an entropy decoder module **420**. The entropy decoder module **420** extracts syntax elements from the bitstream **133** by decoding sequences of 'bins' and passes the values of the syntax elements to other modules in the video decoder **134**. The entropy decoder module **420** uses an arithmetic decoding engine to decode each syntax element as a sequence of one or more bins. Each bin may use one or more 'contexts', with a context describing probability levels to be used for coding a 'one' and a 'zero' value for the bin. Where multiple contexts are available for a given bin, a 'context modelling' or 'context selection' step is performed to choose one of the available contexts for decoding the bin. The process of decoding bins forms a sequential feedback loop. The number of operations in the feedback loop is preferably minimised to enable the entropy decoder **420** to achieve a high throughput in bins/second. Context modelling depends on other properties of the bitstream known to the video decoder **134** at the time of selecting the context, that is, properties preceding the current bin. For example, a context may be selected based on the quad-tree depth of the current CU in the coding tree. Dependencies are preferably based on properties that are known well in advance of decoding a bin, or are determined without requiring long sequential processes.

[0106] A quadtree depth of a coding tree is an example of a dependency for context modelling that is easily known. An intra prediction mode, in particular a matrix intra prediction mode, is an example of a dependency for context modelling and binarisation that is relatively difficult or computationally intensive to determine. Matrix intra prediction modes are coded as either an index into a list of 'most probable modes' (MPMs) or an index into a list of 'remaining modes', with the selection between MPMs and remaining modes according to a decoded context-coded flag. Other intra prediction modes are coded as either an index into a list of 'most probable modes' (MPMs) or an index into a list of 'remaining modes', with the selection between MPMs and remaining modes according to a decoded intra-luma_MPM_flag. When an MPM is in use for coding matrix intra prediction mode a truncated unary bin string with range 0 to 2 selects one of the MPMs from the MPM list. When a remaining mode is in use a fixed-length codeword is decoded to select which

one of the remaining (non-MPM) modes is to be used. The number of available MIP modes is one of 35, 19, or 11, depending on block size. Accordingly, with an MPM list of length 3, the number of remaining modes is 32, 16, or 8, respectively. Remaining modes may be efficiently represented with fixed-length codewords of length 5, 4, or 3, respectively. Determining both the most probable modes and the remaining modes requires a substantial number of operations and includes dependencies on the intra prediction modes of neighbouring blocks. For example, the neighbouring blocks can be the block(s) above and to the left of the current block. If a neighbouring block uses angular intra prediction, a table lookup may be performed to map the angular intra prediction mode into a matrix intra prediction mode for use in populating the MPM list. Alternatively, arrangements may use a truncated binary codeword to encode the MIP modes for each case, that is whether the number of modes is 35, 19, or 11. The entropy decoder module **420** applies an arithmetic coding algorithm, for example ‘context adaptive binary arithmetic coding’ (CABAC), to decode syntax elements from the bitstream **133**. The decoded syntax elements are used to reconstruct parameters within the video decoder **134**. Parameters include residual coefficients (represented by an arrow **424**) and mode selection information such as an intra prediction mode (represented by an arrow **458**). The mode selection information also includes information such as motion vectors, and the partitioning of each CTU into one or more CBs. Parameters are used to generate PBs, typically in combination with sample data from previously decoded CBs.

[0107] The residual coefficients **424** are input to a dequantiser module **428**. The dequantiser module **428** performs inverse quantisation (or ‘scaling’) on the residual coefficients **424** to create reconstructed intermediate transform coefficients, represented by an arrow **432**, according to a quantisation parameter. The reconstructed intermediate transform coefficients **432** are passed to an inverse secondary transform module **436** where a secondary transform is applied or no operation (bypass). The inverse secondary transform module **436** produces reconstructed transform coefficients **440**. Should use of a non-uniform inverse quantisation matrix be indicated in the bitstream **133**, the video decoder **134** reads a quantisation matrix from the bitstream **133** as a sequence of scaling factors and arranges the scaling factors into a matrix. The inverse scaling uses the quantisation matrix in combination with the quantisation parameter to create the reconstructed intermediate transform coefficients **432**.

[0108] The reconstructed transform coefficients **440** are passed to an inverse primary transform module **444**. The module **444** transforms the coefficients from the frequency domain back to the spatial domain. The result of operation of the module **444** is a block of residual samples, represented by an arrow **448**. The block of residual samples **448** is equal in size to the corresponding CU. The residual samples **448** are supplied to a summation module **450**. At the summation module **450** the residual samples **448** are added to a decoded PB (represented as **452**) to produce a block of reconstructed samples, represented by an arrow **456**. The reconstructed samples **456** are supplied to a reconstructed sample cache **460** and an in-loop filtering module **488**. The in-loop filtering module **488** produces reconstructed blocks of frame samples, represented as **492**. The frame samples **492** are written to a frame buffer **496**.

[0109] The reconstructed sample cache **460** operates similarly to the reconstructed sample cache **356** of the video encoder **114**. The reconstructed sample cache **460** provides storage for reconstructed sample needed to intra predict subsequent CBs without the memory **206** (for example by using the data **232** instead, which is typically on-chip memory). Reference samples, represented by an arrow **464**, are obtained from the reconstructed sample cache **460** and supplied to a reference sample filter **468** to produce filtered reference samples indicated by arrow **472**. The filtered reference samples **472** are supplied to an intra-frame prediction module **476**. The module **476** produces a block of intra-predicted samples, represented by an arrow **480**, in accordance with the intra prediction mode parameter **458** signalled in the bitstream **133** and decoded by the entropy decoder **420**. The block of samples **480** is generated using modes such as DC, planar or angular intra prediction but not matrix intra prediction.

[0110] When the prediction mode of a CB is indicated to use intra prediction (other than matrix intra prediction) in the bitstream **133**, the intra-predicted samples **480** form the decoded PB **452** via a multiplexor module **484**. Intra prediction produces a prediction block (PB) of samples, that is, a block in one colour component, derived using ‘neighbouring samples’ in the same colour component. The neighbouring samples are samples adjacent to the current block and by virtue of being preceding in the block decoding order have already been reconstructed. Where luma and chroma blocks are collocated, the luma and chroma blocks may use different intra prediction modes. However, the two chroma channels each share the same intra prediction mode. Intra prediction falls into three types. “DC intra prediction” involves populating a PB with a single value representing the average of the neighbouring samples. “Planar intra prediction” involves populating a PB with samples according to a plane, with a DC offset and a vertical and horizontal gradient being derived from the neighbouring samples. “Angular intra prediction” involves populating a PB with neighbouring samples filtered and propagated across the PB in a particular direction (or ‘angle’). In VVC 65 angles are supported, with rectangular blocks able to utilise additional angles, not available to square blocks, to produce a total of 87 angles. A fourth type of intra prediction is available to chroma PBs, whereby the PB is generated from collocated luma reconstructed samples according to a ‘cross-component linear model’ (CCLM) mode. Three different CCLM modes are available, each of which uses a different model derived from the neighbouring luma and chroma samples. The derived model is then used to generate a block of samples for the chroma PB from the collocated luma samples.

[0111] When the prediction mode of the CB is indicated to be matrix intra prediction in the bitstream **133**, a matrix intra prediction mode **458** is decoded and supplied to a coefficient memory **486** and a matrix intra prediction module **482**. Matrix coefficients **481** are read from the coefficient memory **486** for the selected matrix intra prediction mode and passed to the matrix intra prediction module **482**. Selection of matrix coefficients involves memory read operations from the coefficient memory **486**, with a worst case memory bandwidth limit of the memory accesses established by the frequency of selection of MIP mode for given block sizes, as described with reference to FIGS. **8** and **9**.

[0112] When the prediction mode of the CB is indicated to be inter prediction in the bitstream **133**, a motion compensation module **434** produces a block of inter-predicted samples, represented as **438**, using a motion vector and reference frame index to select and filter a block of samples **498** from a frame buffer **496**. The block of samples **498** is obtained from a previously decoded frame stored in the frame buffer **496**. For bi-prediction, two blocks of samples are produced and blended together to produce samples for the decoded PB **452**. The frame buffer **496** is populated with filtered block data **492** from an in-loop filtering module **488**. As with the in-loop filtering module **368** of the video encoder **114**, the in-loop filtering module **488** applies any of the DBF, the ALF and SAO filtering operations. Generally, the motion vector is applied to both the luma and chroma channels, although the filtering processes for sub-sample interpolation luma and chroma channel are different.

[0113] FIG. **5** is a schematic block diagram showing a collection **500** of available divisions or splits of a region into one or more sub-regions in the tree structure of versatile video coding. The divisions shown in the collection **500** are available to the block partitioner **310** of the encoder **114** to divide each CTU into one or more CUs or CBs according to a coding tree, as determined by the Lagrangian optimisation, as described with reference to FIG. **3**.

[0114] Although the collection **500** shows only square regions being divided into other, possibly non-square sub-regions, it should be understood that the diagram **500** is showing the potential divisions but not requiring the containing region to be square. If the containing region is non-square, the dimensions of the blocks resulting from the division are scaled according to the aspect ratio of the containing block. Once a region is not further split, that is, at a leaf node of the coding tree, a CU occupies that region. The particular subdivision of a CTU into one or more CUs by the

block partitioner **310** is referred to as the ‘coding tree’ of the CTU.

[0115] The process of subdividing regions into sub-regions must terminate when the resulting sub-regions reach a minimum CU size. In addition to constraining CUs to prohibit block areas smaller than a predetermined minimum size, for example 16 samples, CUs are constrained to have a minimum width or height of four. Other minimums, both in terms of width and height or in terms of width or height are also possible. The process of subdivision may also terminate prior to the deepest level of decomposition, resulting in a CU larger than the minimum CU size. It is possible for no splitting to occur, resulting in a single CU occupying the entirety of the CTU. A single CU occupying the entirety of the CTU is the largest available coding unit size. Due to use of subsampled chroma formats, such as 4:2:0, arrangements of the video encoder **114** and the video decoder **134** may terminate splitting of regions in the chroma channels earlier than in the luma channels.

[0116] At the leaf nodes of the coding tree exist CUs, with no further subdivision. For example, a leaf node **510** contains one CU. At the non-leaf nodes of the coding tree exist a split into two or more further nodes, each of which could be a leaf node that forms one CU, or a non-leaf node containing further splits into smaller regions. At each leaf node of the coding tree, one coding block exists for each colour channel. Splitting terminating at the same depth for both luma and chroma results in three collocated CBs. Splitting terminating at a deeper depth for luma than for chroma results in a plurality of luma CBs being collocated with the CBs of the chroma channels.

[0117] A quad-tree split **512** divides the containing region into four equal-size regions as shown in FIG. 5. Compared to HEVC, versatile video coding (VVC) achieves additional flexibility with the addition of a horizontal binary split **514** and a vertical binary split **516**. Each of the splits **514** and **516** divides the containing region into two equal-size regions. The division is either along a horizontal boundary (**514**) or a vertical boundary (**516**) within the containing block.

[0118] Further flexibility is achieved in versatile video coding with addition of a ternary horizontal split **518** and a ternary vertical split **520**. The ternary splits **518** and **520** divide the block into three regions, bounded either horizontally (**518**) or vertically (**520**) along $\frac{1}{4}$ and $\frac{3}{4}$ of the containing region width or height. The combination of the quad tree, binary tree, and ternary tree is referred to as ‘QTBT-TT’. The root of the tree includes zero or more quadtree splits (the ‘QT’ section of the tree). Once the QT section terminates, zero or more binary or ternary splits may occur (the ‘multi-tree’ or ‘MT’ section of the tree), finally ending in CBs or CUs at leaf nodes of the tree. Where the tree describes all colour channels, the tree leaf nodes are CUs. Where the tree describes the luma channel or the chroma channels, the tree leaf nodes are CBs.

[0119] Compared to HEVC, which supports only the quad tree and thus only supports square blocks, the QTBT-TT results in many more possible CU sizes, particularly considering possible recursive application of binary tree and/or ternary tree splits. The potential for unusual (non-square) block sizes can be reduced by constraining split options to eliminate splits that would result in a block width or height either being less than four samples or in not being a multiple of four samples. Generally, the constraint would apply in considering luma samples. However, in the arrangements described, the constraint can be applied separately to the blocks for the chroma channels.

Application of the constraint to split options to chroma channels can result in differing minimum block sizes for luma versus chroma, for example when the frame data is in the 4:2:0 chroma format or the 4:2:2 chroma format. Each split produces sub-regions with a side dimension either unchanged, halved or quartered, with respect to the containing region. Then, since the CTU size is a power of two, the side dimensions of all CUs are also powers of two.

[0120] FIG. 6 is a schematic flow diagram illustrating a data flow **600** of a QTBT-TT (or ‘coding tree’) structure used in versatile video coding. The QTBT-TT structure is used for each CTU to define a division of the CTU into one or more CUs. The QTBT-TT structure of each CTU is determined by the block partitioner **310** in the video encoder **114** and encoded into the bitstream **115** or decoded from the bitstream **133** by the entropy decoder **420** in the video decoder **134**. The

data flow **600** further characterises the permissible combinations available to the block partitioner **310** for dividing a CTU into one or more CUs, according to the divisions shown in FIG. 5.

[0121] Starting from the top level of the hierarchy, that is at the CTU, zero or more quad-tree divisions are first performed. Specifically, a Quad-tree (QT) split decision **610** is made by the block partitioner **310**. The decision at **610** returning a '1' symbol indicates a decision to split the current node into four sub-nodes according to the quad-tree split **512**. The result is the generation of four new nodes, such as at **620**, and for each new node, recursing back to the QT split decision **610**. Each new node is considered in raster (or Z-scan) order. Alternatively, if the QT split decision **610** indicates that no further split is to be performed (returns a '0' symbol), quad-tree partitioning ceases and multi-tree (MT) splits are subsequently considered.

[0122] Firstly, an MT split decision **612** is made by the block partitioner **310**. At **612**, a decision to perform an MT split is indicated. Returning a '0' symbol at decision **612** indicates that no further splitting of the node into sub-nodes is to be performed. If no further splitting of a node is to be performed, then the node is a leaf node of the coding tree and corresponds to a CU. The leaf node is output at **622**. Alternatively, if the MT split **612** indicates a decision to perform an MT split (returns a '1' symbol), the block partitioner **310** proceeds to a direction decision **614**.

[0123] The direction decision **614** indicates the direction of the MT split as either horizontal ('H' or '0') or vertical ('V' or '1'). The block partitioner **310** proceeds to a decision **616** if the decision **614** returns a '0' indicating a horizontal direction. The block partitioner **310** proceeds to a decision **618** if the decision **614** returns a '1' indicating a vertical direction.

[0124] At each of the decisions **616** and **618**, the number of partitions for the MT split is indicated as either two (binary split or 'BT' node) or three (ternary split or 'TT') at the BT/TT split. That is, a BT/TT split decision **616** is made by the block partitioner **310** when the indicated direction from **614** is horizontal and a BT/TT split decision **618** is made by the block partitioner **310** when the indicated direction from **614** is vertical.

[0125] The BT/TT split decision **616** indicates whether the horizontal split is the binary split **514**, indicated by returning a '0', or the ternary split **518**, indicated by returning a '1'. When the BT/TT split decision **616** indicates a binary split, at a generate HBT CTU nodes step **625** two nodes are generated by the block partitioner **310**, according to the binary horizontal split **514**. When the BT/TT split **616** indicates a ternary split, at a generate HTT CTU nodes step **626** three nodes are generated by the block partitioner **310**, according to the ternary horizontal split **518**.

[0126] The BT/TT split decision **618** indicates whether the vertical split is the binary split **516**, indicated by returning a '0', or the ternary split **520**, indicated by returning a '1'. When the BT/TT split **618** indicates a binary split, at a generate VBT CTU nodes step **627** two nodes are generated by the block partitioner **310**, according to the vertical binary split **516**. When the BT/TT split **618** indicates a ternary split, at a generate VTT CTU nodes step **628** three nodes are generated by the block partitioner **310**, according to the vertical ternary split **520**. For each node resulting from steps **625-628** recursion of the data flow **600** back to the MT split decision **612** is applied, in a left-to-right or top-to-bottom order, depending on the direction **614**. As a consequence, the binary tree and ternary tree splits may be applied to generate CUs having a variety of sizes.

[0127] FIGS. 7A and 7B provide an example division **700** of a CTU **710** into a number of CUs or CBs. An example CU **712** is shown in FIG. 7A. FIG. 7A shows a spatial arrangement of CUs in the CTU **710**. The example division **700** is also shown as a coding tree **720** in FIG. 7B.

[0128] At each non-leaf node in the CTU **710** of FIG. 7A, for example nodes **714**, **716** and **718**, the contained nodes (which may be further divided or may be CUs) are scanned or traversed in a 'Z-order' to create lists of nodes, represented as columns in the coding tree **720**. For a quad-tree split, the Z-order scanning results in top left to right followed by bottom left to right order. For horizontal and vertical splits, the Z-order scanning (traversal) simplifies to a top-to-bottom scan and a left-to-right scan, respectively. The coding tree **720** of FIG. 7B lists all nodes and CUs according to the applied scan order. Each split generates a list of two, three or four new nodes at the next level of the

tree until a leaf node (CU) is reached.

[0129] Having decomposed the image into CTUs and further into CUs by the block partitioner **310**, and using the CUs to generate each residual block (**324**) as described with reference to FIG. 3, residual blocks are subject to forward transformation and quantisation by the video encoder **114**. The resulting TBs **336** are subsequently scanned to form a sequential list of residual coefficients, as part of the operation of the entropy coding module **338**. An equivalent process is performed in the video decoder **134** to obtain TBs from the bitstream **133**.

[0130] As a result of the splits of a CTU into CUs, small-sized CUs (such as 4×4 , 4×8 , or 8×4) appear spatially adjacent in the frame. Moreover, small-sized CUs are processed temporally adjacently, by virtue of a hierarchical Z-order scan of the coding tree. In particular, a quadtree split of an 8×8 region results in a sequence of four 4×4 CUs, a binary split of an 8×4 or 4×8 region results in a pair of 4×4 CUs, and a binary split of an 8×8 region results in either a pair of 4×8 regions or a pair of 8×4 regions. Each resulting region (of size 4×8 or 8×4) can form either a CU or can be further split into 4×4 CUs. A ternary split applied in an area of 64 samples results in three regions of sizes 16, 32, and 16, that is. 4×4 , 4×8 or 8×4 , and 4×4 . A ternary split applied in an area of 128 samples results in three regions of size 32, 64, and 32 samples, for example 4×8 , 8×8 , and 4×8 regions. Small blocks (for example 4×4 , 4×8 , 8×4) are seen together, both spatially and in the Z-order scan through the CTU, as they are the result of splitting regions of sizes such as 64 or 128.

[0131] FIG. 8 shows a dataflow **800** providing detail of operation of the matrix intra prediction modules **390** and **482** of the video encoder **114** and the video decoder **134**, respectively, using an 8×8 block. Matrix intra prediction is only performed in the luma channel in the example of FIG. 8, and so different block sizes resulting from the use of chroma formats such as 4:2:0 or 4:2:2 do not need to be considered. The modules **390** and **482** output a block of matrix predicted samples, such as **393** or **483** respectively. The block **393** serves as the PB **320** in the video encoder **114** when the mode selector **386** selects matrix intra prediction for a CU. The block **483** serves as the PB **483** when matrix intra prediction is indicated for use by decoding a prediction mode for the CU from the bitstream **133**.

[0132] Operation of the modules **390** and **482** involves three steps: 1. Averaging, 2. Matrix multiplication and offset (bias) addition, and 3. Bilinear interpolation. Bilinear interpolation is performed only when CU size is larger than 4×4 . The averaging step operates as follows. Reference samples **802** (for example **358** or **464**), are received at the dataflow **800** and assigned as above samples **822** and left samples **820**. When the width and height of the luma CB is greater than four the above samples **822** are divided into four sets (four pairs in the example 8×8 block of FIG. 8). The values of the contents each of the four sets are averaged to produce four filtered above samples **826**. Similarly, the left samples **820** are divided into four sets (four pairs in the example 8×8 block of FIG. 8). The values of the contents each of the four sets are averaged to produce four filtered left samples **824**. Accordingly, a total of eight filtered samples as input to a matrix multiply module **828**.

[0133] When the block width and height is equal to four (rather than 8 as shown in FIG. 8), the four above samples **822** are divided into two pairs, each of which is averaged to produce two above filtered samples **826**. Similarly, the four left samples **820** are divided into two pairs, each of which is averaged to produce two left filtered samples **824**, for a total of four filtered samples as input to the matrix multiply module **828**.

[0134] In the second step (matrix multiplication) received matrix coefficients, (**363** or **481**), are selected according to the matrix intra prediction mode (**388** or **458**), are also input to the matrix multiply module **828**. Also input to the matrix multiply module are a set of offset or bias values. The offset or bias values are added to the result of the matrix multiply to introduce any desired DC shift. The matrix coefficients and bias values are predetermined. In other words, the matrix coefficients and bias values are the result of an 'offline' training process and are considered to be constant values by the video encoder **114** and the video decoder **134**.

[0135] For 4×4 CBs, 35 MIP modes are available, with 18 sets of matrix coefficients and bias values (set A). For 4×8 , 8×4 , and 8×8 CBs, 19 MIP modes are available, with 10 sets of matrix coefficients and bias values (set B). For other CB sizes, 11 MIP modes are available, with 6 sets of matrix coefficients and bias values (set C). A given set of matrix coefficients and bias values may be used for two MIP modes. One MIP mode uses the provided values and another MIP modes uses a transpose of the provided values. Further, in one case a set of matrix coefficients and bias values is dedicated to a single MIP mode. Each of the three cases applies to each of sets A-C. The sets A-C are sized as follows, also shown is the number of words selected by **362** or **481** for use in generating one PB (i.e. application of MIP mode to one CU) given for each of sets A-C: [0136] Set A: 18 matrices of size 16×4 , 18 offset vectors of size 16. Size of selected values for CB is: $16\times 4+16=80$ words. [0137] Set B: 10 matrices of size 16×8 , 10 offset vectors of size 16. Size of selected values for CB is $16\times 8+16=144$ words. [0138] Set C: 6 matrices of size 64×8 , 10 offset vectors of size 64. Size of selected values for CB is $64\times 8+64=576$ words.

[0139] The video encoder **114** and the video decoder **134** process video data at a pixel rate determined by the frame size and frame rate. Additionally, luma CB sizes are multiples of four in width and height. Accordingly, the memory bandwidth requirement for sets A-C can be expressed in terms of accesses for 4×4 luma samples. Access densities for each of sets A-C for worst case, i.e. smallest, block sizes for the respective set when no constraint on the usage of MIP mode to each CU is in place are as follows: [0140] Set A: 4×4 CB requires 80 words per 4×4 sample area. [0141] Set B: 4×8 and 8×4 CB requires $144\div 2=72$ words per 4×4 sample area, 8×8 CB requires $144\div 4=36$ words per 4×4 sample area. [0142] Set C: 8×16 and 16×8 CB requires $576-8-72$ words per 4×4 sample area, 8×32 , 16×16 , 32×8 CB requires $576-16=36$ words per 4×4 sample area, larger CB size requires fewer words per 4×4 sample area.

[0143] As shown by the access densities above, when no constraint upon the usage of MIP mode is in place, in the worst case all CBs may use MIP mode and the coding tree may decompose each CTU into the small CB sizes used above to illustrate worst-case coefficient memory (**486**, **392**) bandwidth. The nominal word size for matrix coefficients and bias values is 16 bits, although fewer bits, for example 10 bits, may be adequate. Fetching of words in groups is a likely implementation choice. Nevertheless, the memory bandwidth burden remains somewhat high.

[0144] Statistics of MIP mode selection show that typically, in 20% of cases over a wide test set (as defined in the JVET common test conditions document JVET-N1010), MIP mode is selected for adjacently located CBs, when considering the above and left blocks. Thus, restriction on the frequency of application of MIP mode is possible to alleviate the worst case memory bandwidth required for the coefficient memories **486** and **392**, without causing a commensurate reduction in the compression efficiency gain seen from the availability of MIP mode. The constraints on MIP mode selection are described with reference to FIGS. **11-16**.

[0145] The matrix multiply module **828** performs the matrix multiply using the set of matrix coefficients (**363** or **481**) and the filtered reference samples (i.e. **824** and **826**). Bias values are added to the output of the matrix multiply, forming a sparse block **830**. The sparse block **830** is shown as shaded samples partially populating **393** or **483**. The remainder of the samples of **393** or **483** are derived using bilinear interpolation, with contribution from either the above reference samples **822** and the left filtered reference samples **824** or the left reference samples **820** and the above filtered samples **822** (as shown in FIG. **8**).

[0146] FIG. **9A** shows an example CTU **900**. The CTU **900** has regions within which memory access bandwidth for MIP mode is applied. Matrix intra prediction is applied within VPDU-sized regions, i.e. 64×64 quadrants of the 128×128 CTU **900**. For example, 512 luma sample regions for which a budget applies include (i) a 32×16 region **912**, (ii) a 16×32 region **914**, and (iii) a 64×8 region **916**. The region **912** is further decomposed into a variety of CUs, i.e. **912a-912h** in FIG. **9B**. In the example of FIG. **9B**, the CU **912a** is of size 16×4 and thus belongs to Set C, the CU **912d** is of size 8×8 and thus belongs to set B, as do **912b**, **912c**, and **912e** (all of size 8×4). The CUs **912f**

and **912g** are each 4×4 and thus belong to set A. As described in relation to FIGS. **11** to **16**, a region area of 512 luma samples can be used in the arrangements described as a threshold to determine whether to apply a constraint for MIP mode. Using a region area of 512 samples is suitable as a constraint as the sets A to C, described above, can typically result from splits of the region. However, the threshold may relate to a different area as described hereafter.

[0147] FIG. **10** shows a coding tree **1000** corresponding to the example CTU **900** of FIG. **9A**. The region **912** corresponds to a node in the coding tree at which a budget for the contained CUs is established for MIP matrix coefficient reading, as do the regions **914** and **916**. Decomposition into one or more CUs in the regions is not shown for ease of reference. For each CU configured to use MIP mode, the quantity of budget according to the CUs size mapping to one of Sets A-C is deducted from the region (i.e. **912**, **914**, **916**) budget, as described below with reference to FIGS. **11-16**.

[0148] FIG. **11** shows a method **1100** for encoding coding units of an image frame into a video bitstream **115**. The method **1100** may be embodied by apparatus such as a configured FPGA, an ASIC, or an ASSP. Additionally, the method **1100** may be performed by the video encoder **114** under execution of the processor **205**. As such, the method **1100** may be stored on computer-readable storage medium and/or in the memory **206**. Performance of the method **1100** to encode an image frame as a sequence of coding units into the bitstream **115** that applies a constraint to use of matrix intra prediction. Operation of the method **1100** therefore results in a restriction on the memory bandwidth needed for matrix intra prediction compared to a worst case potential memory bandwidth, as would be the case were no constraint in place. The method **1100** commences at a divide frame into CTUs step **1110**.

[0149] At the divide frame into CTUs step **1110** the block partitioner **310**, under execution of the processor **205**, divides a current frame of the frame data **113** into an array of CTUs. A progression of encoding over the CTUs resulting from the division commences. Control in the processor progresses from the step **1110** to a determine coding tree step **1120**.

[0150] At the determine coding tree step **1120** the video encoder **114**, under execution of the processor **205**, tests various split options, as described with reference to FIGS. **5-7**, in combination with the operation of a determine coding unit step **1130** to arrive at a coding tree for a CTU. Operation of the step **1120** is described with reference to FIG. **12**. Control in the processor **205** progresses from the step **1120** to the determine prediction mode for coding unit step **1130**.

[0151] At the determine coding unit step **1130** the video encoder **114**, under execution of the processor **205**, determines the prediction mode to be used in encoding a selected coding unit into the bitstream **115**. The coding units may be selected according to a scan pattern. Operation of the step **1130** is described further with reference to FIG. **13**. Once a prediction mode has been selected for a coding unit, control in the processor **205** progresses from the step **1130** to an encode coding unit step **1140**. In selecting prediction modes for coding units, with the coding units themselves resulting from the hierarchy of splits of the coding tree, the particular combination of splits to arrive at a given coding unit is also selected and thus the coding tree is determined.

[0152] At the encode coding unit step **1140** the entropy encoder **338**, under execution of the processor **205**, encodes the coding unit determined at step **1130** into the bitstream **115**. The determined coding tree is effectively encoded into the bitstream **115** at step **1140** by the entropy encoder **338**, under execution of the processor **205**, using ‘split flags’ and other syntax elements to indicate the selected splits, as shown in FIGS. **5** and **6**.

[0153] Operation at the step **1140** is described further with reference to FIG. **14**. Control in the processor **205** progresses from the step **1140** to a last coding unit test step **1150**.

[0154] At the last coding unit test step **1150** the processor **205** tests if the current coding unit is the last coding unit in the coding tree of step **1120**. If the current coding unit is the last in the coding tree of step **1120** (“YES” at step **1150**), control in the processor **205** progresses to a last CTU test step **1160**. If the current coding unit is not the last one in the coding tree of step **1120** (“NO” at step

1150), the next coding unit in the coding tree of step **1120** is selected using the scan pattern for determination and encoding and control in the processor **205** progresses to the step **1130**. The step **1130** is accordingly performed for each CU resulting from the coding tree determined at the step **1120**.

[0155] At the last CTU test step **1160** the processor **205** tests if the current CTU is the last CTU in the slice or frame. If not (“NO” at step **1160**), the video encoder **114** advances to the next CTU in the frame and control in the processor **205** progresses from the step **1160** back to the step **1120** to continue processing remaining CTUs in the frame. If the CTU is the last in the frame or slice, the step **1160** returns “YES” and the method **1100** terminates. As a result of operation of the method **1100**, an entire image frame is encoded as a sequence of CTUs into a bitstream.

[0156] The method **1100** is performed on each image frame in the video sequence. The method **1100** may determine CUs on a CTU-by-CTU basis. In other words, the CUs of a CTU may firstly be determined in one pass or pipeline stage, followed by a second stage for encoding into the bitstream **115**. The method **1100** may also determine CUs at a finer granularity, for example, on a VPDU-by-VPDU basis, for reduced memory consumption due to the smaller area of a VPDU compared to a CTU.

[0157] FIG. **12** shows a method **1200** for determining a coding tree for a CTU as implemented at step **1120**. The method **1200** executes to receive a CTU and generating candidate splits and candidate coding units for evaluation and eventual selection as splits and coding units to be encoded in the bitstream **115**. In particular, the method **1200** establishes a budget for MIP mode memory bandwidth at particular nodes or regions in the coding tree that constrain application of MIP mode in coding units below the node, i.e. within the spatial region. The method **1200** may be embodied by apparatus such as a configured FPGA, an ASIC, or an ASSP. Additionally, the method **1200** may be performed by video encoder **114** under execution of the processor **205**. As such, the method **1200** may be stored on computer-readable storage medium and/or in the memory **206**. The method **1200** is invoked for each node (region) in a candidate coding tree. The method **1200** commences at a region area test step **1210**.

[0158] At the region area test step **1210** the video encoder **114**, under execution of the processor **205**, tests the area occupied by a candidate node in the coding tree according to available split options (using the split options described in relation to FIG. **5**). In the context of the arrangements described, a region relates to a node in the coding tree that may further splits before splitting ceases, causing CUs to be formed. The region need not correspond with the direct parent of the current coding unit, i.e. the parent region for which the MIP mode memory access bandwidth budget was set may be multiple nodes above the present node in the coding tree. For example, a region of 512 luma samples may be split into many small coding units, for example of sizes such as 4×4, 4×8, 8×4. As the encoder search progresses, different candidate nodes resulting from candidate splits are tested. Within each candidate nodes, various prediction modes for the resulting coding units are tested. When the area in luma samples occupied by a region is does not satisfy a threshold, the region area test evaluates as TRUE and control in the processor **205** progresses from the step **1210** to a set budget step **1220**. When the area in luma samples occupied by the region is satisfies the threshold, the region area test evaluates as FALSE and control in the processor **205** progresses from the step **1210** to a generate splits step **1230**. In one implementation, as described in an example of FIGS. **11** to **16**, the threshold is 512 samples and is satisfied when the region has an area greater than 512 samples. Other thresholds may be used as described below. The threshold is typically predetermined, based on required performance of the encoder **114** and the decoder **134**.

[0159] At the set budget step **1220** the video encoder **114**, under execution of the processor **205**, sets a budget for a region corresponding to the area of the current node in the coding tree. This budget is available to any sub-nodes (sub-regions) within the current region that result from splitting the current region into smaller regions. For all regions less than or equal to 512 luma samples, the budget may be considered in the application of MIP mode when coding unit prediction

modes are being evaluated. An area of 512 luma samples may be subject to a ternary split for example, resulting in coding units of areas 128, 256, and 128 luma samples. The coding units of area 128 luma samples may have dimensions of 8×16 or 16×8 , in which case a worst case memory bandwidth limit may be reached, resulting in prohibition of use of MIP mode for other coding units in the region, including those resulting from further subdivision of the region. When an area of 512 luma samples is binary split into two coding units of 256 luma sample area, for example 16×16 , the worst case memory bandwidth limit is not reached and there is no constraint on the usage of MIP mode for the resulting CUs. However, further divisions of each 256-sample area region into smaller CUs, i.e., CUs of sizes 16×8 , 8×16 , 8×8 , 8×4 , 4×8 , and 4×4 , may result in constraining the usage of MIP mode for the later resulting CUs due to consumption of the budget by earlier resulting CUs.

[0160] The budget may be expressed as a maximum word reads per 4×4 block area, since 4×4 is the size of the smallest luma coding unit and all other coding units are integer multiples of this size and thus all regions are also multiples of this size. The budget may be 40 word reads for 4×4 block, which for a 512 luma sample area corresponds to $(512 = (4 \times 4)) \times 40 = 1280$ word reads as the maximum number of permitted read operations in the 512 luma sample region. Each time MIP mode is used for a CU, the required number of reads is deducted from the budget and when the budget is insufficient for further usage of MIP mode, further CUs are prohibited from using the MIP mode as described in relation to FIGS. 13 and 14. In this manner, larger sized CUs may use MIP mode, for example a single CU of area 512 samples or a pair of CUs of area 256 samples may use MIP mode without any restriction being introduced from the constraint. When the coding tree decomposes the area of 512 samples into a larger number of smaller CUs, consumption of the budget may prohibit further CUs in the region from using MIP mode. A 512 sample area with a budget of 40 words per 4×4 results in a total budget for the region of $512 = (4 \times 4) \times 40 = 1280$ words. In a division of the 512 sample area into four CUs of sizes 8×16 or 16×8 , use of MIP mode by two of the CUs consumes 576 words per CU, or 1152 words. The remaining budget of 128 word reads is insufficient for the other two CUs in the region to use MIP mode. Control in the processor 205 progresses from the step 1220 to a generate splits step 1230.

[0161] At the generate splits step 1230 the block partitioner 310, under execution of the processor 205, generates a set of candidate splits for the current node in the coding tree. The splits are as shown in FIG. 5, and the associated syntax elements are shown in FIG. 6 and exemplified in FIG. 7. In the case of generation of a 'no split', i.e. 510, a coding unit is later generated. In the case of generation of other types of split, i.e. 512-520, additional nodes in the coding tree are generated according to each split. The method 1200 is repeated to generate coding units for the additional nodes when 'no split' cases are generated on the later traversals of the method 1200. The method 1200 is repeated for each node of the CTU in order. Accordingly, all splits for the CTU are determined. Moreover, the recursive nature of this generation of splits within splits results in searching all possible coding units in a given CTU, within constraints on minimum CU size and depth recursion constraints that may limit the number of recursions using binary, ternary, and quadtree splits. Control in the processor 205 progresses from the step 1230 to a generate CU step 1240.

[0162] At the generate CU step 1240 the block partitioner 310, under execution of the processor 205, generates a candidate CU for each case where a 'no split' was generated at the generate splits step 1230. At the step 1240 the prediction mode of the candidate CU is yet to be determined but the prediction modes of the CUs preceding in the Z-order scan are known, although the final modes are not yet chosen. Thus, neighbouring (in terms of location in the CU) reference samples are available for intra prediction either from adjacent CUs that may be from the same split operation as the split containing the current CU, or from neighbouring regions resulting from different parent regions, or from different CTUs altogether. The step 1240 effectively splits a region of the coding tree into coding blocks, each of the coding blocks including a prediction block as described in relation to FIG. 3. The method 1200 terminates at the step 1240, with control in the processor 205 returning to

the method **1100** where the prediction mode of the generated CU is determined.

[0163] FIG. **13** shows a method **1300** for determining a coding unit as implemented at step **1130**. The method **1300** involves determining a prediction mode for a coding unit as generated by performing the method **1200**. The prediction mode includes intra prediction, inter prediction and MIP mode according to a budget for use of MIP mode within a region containing the current coding unit. The budget established in the method **1200** is used to control whether MIP mode is to be tested or not for the current CU. A portion of the budget is consumed every time a CU in the region is of size of a worst case block (as described in relation to cases A-C above), dependent upon the number of code words in the CU. Once the budget is consumed, further coding units in the region are not searched for potential use of the MIP mode, i.e. invocation of the method **1300** only performs testing of MIP modes when earlier invocations of the method **1300** have not exhausted the memory access bandwidth budget was set applied to a common parent node in the coding tree.

[0164] The region need not correspond with the direct parent of the current coding unit, i.e. the parent region for which the MIP mode memory access bandwidth budget was set may be multiple nodes above the present node in the coding tree. For example, a region of 512 luma samples may be split into many small coding units, for example of sizes such as 4×4, 4×8, 8×4. For each CU, the use of MIP mode is constrained by the remaining budget for the region of 512 luma samples. The method **1300** may be implemented by the mode selector **386**, or in part by the module **3960**. The method **1300** may be embodied by apparatus such as a configured FPGA, an ASIC, or an ASSP. Additionally, the method **1300** may be performed by video encoder **114** under execution of the processor **205**. As such, the method **1300** may be stored on computer-readable storage medium and/or in the memory **206**. The method **1300** commences at a test intra prediction modes step **1310**.

[0165] At the test intra prediction modes step **1310** the video encoder **114**, under execution of the processor **205**, tests ‘regular’ intra prediction modes, i.e. DC, planar, and angular intra prediction modes, for potential use in coding the current coding unit. Generally, a Lagrangian optimisation is performed to select the optimal intra prediction mode among the available intra prediction modes for the CU. Application of the secondary transform, i.e. **330** and **344**, is also tested, as are different types of primary transform (DCT-2, DCT-8, DST-7) including a transform skip case. Control in the processor **205** progresses from the step **1310** to a test inter prediction modes step **1320**.

[0166] At the test inter prediction modes step **1320** the video encoder **114**, under execution of the processor **205**, tests various motion vectors for generating inter predicted PUs. When evaluating use of inter prediction, a motion vector is selected from a set of candidate motion vectors.

Candidate motion vectors are generated according to a search pattern. When testing distortion of fetched reference blocks for candidate motion vectors are being evaluated, the application of prohibited chroma splitting in the coding tree is considered. If a split is prohibited in chroma and allowed in luma, the resulting luma CBs may use inter prediction. Motion compensation is applied to the luma channel only and so the distortion computation considers the luma distortion and not the chroma distortion. The chroma distortion is not considered as motion compensation is not performed in the chroma channel when the chroma split was prohibited. For chroma, the distortion resulting from the considered intra prediction mode and a coded chroma TB (if any) is considered. In considering both luma and chroma, the inter prediction search may firstly select a motion vector based on luma distortion and then ‘refine’ the motion vector by also considering chroma distortion. Refinement generally considers small variation on motion vector value, such as sub-pixel displacements. Particular motion vectors may be those that are generated by ‘merge modes’, whereby the motion vector for the current CU is derived from the motion vector from neighbouring CUs. Merge modes are more compactly expressed in the bitstream syntax compared to other motion vectors that may require signalling of a ‘motion vector delta’, applied relative to a selected ‘motion vector predictor’. The motion vector predictor is generally derived from spatially or temporally neighbouring CUs. For an intra-coded slice, for example the first frame of a sequence of

frames, inter prediction is not available and the step **1320** is not performed. Control in the processor **205** progresses from the step **1320** to a within budget test step **1330**.

[0167] At the within budget test step **1330** the video encoder **114**, under execution of the processor **205**, tests if a MIP mode memory access bandwidth budget is applicable to the current CU. The test executed at **1330** determines if the current CU is contained within a 512 luma sample region for which a MIP mode budget was established at the step **1220**. If the current CU is larger than the 512 luma sample region, there is no applicable budget constraint. Accordingly, the CU is not subject to further constraint upon the usage of MIP mode and control in the processor **205** progresses to a test MIP modes step **1340** (“TRUE” at **1330**). If the current CU is equal in size or smaller than 512 luma samples, the required budget to use MIP mode for the current CU, as described with reference to FIG. **8**, is compared against the remaining budget for the region. If insufficient budget is available to apply MIP mode to the current CU, control in the processor **205** progresses from step **1330** to a select mode step **1350** (“FALSE” at step **1330**). If sufficient budget is available to apply MIP mode to the current CU (“TRUE” at step **1340**) control in the processor **205** progresses from step **1330** to step **1340**.

[0168] At the test MIP modes step **1340** the mode selector **386** tests various MIP modes to determine a best MIP mode for use for predicting the current CU, among the available MIP modes for the size of the CU. As with testing intra prediction modes at step **1310**, a Lagrangian optimisation may be performed to trade-off distortion against coding cost of the tested MIP modes and their associated residuals. Control in the processor **205** progresses from the step **1340** to a select mode step **1350**.

[0169] At the select mode step **1350** the mode selector **386**, under execution of the processor **205**, selects a final mode for the CU from the candidates resulting from the steps **1310**, **1320**, and **1350**. The method **1300** terminates with control in the processor **205** returning to the method **1100**.

[0170] FIG. **14** shows a method **1400** for encoding a coding unit of a coding tree of a CTU into the video bitstream **115**, as implemented at step **1140**. The method **1400** may be embodied by apparatus such as a configured FPGA, an ASIC, or an ASSP. Additionally, the method **1400** may be performed by video encoder **114** under execution of the processor **205**, for example by the entropy encoder **338**. As such, the method **1400** may be stored on computer-readable storage medium and/or in the memory **206**. The method **1400** commences at an encode prediction mode step **1410**.

[0171] At the encode prediction mode step **1410** the entropy encoder **338**, under execution of the processor **205**, encodes a flag using a context coded bin indicating the use of either intra prediction (including both regular intra prediction mode use or MIP mode use) or inter prediction, as determined at the step **1350** and represented by the prediction mode **387**. Encoding of the flag at step **1410** does not distinguish between regular intra prediction and MIP mode. The distinction between regular intra prediction and MIP intra prediction (when applicable) is encoded at an encode MIP mode flag step **1430**. Control in the processor **205** progresses from the step **1410** to a budget test step **1420**.

[0172] At the budget test step **1420** the video encoder **114**, under execution of the processor **205**, tests if a MIP mode memory access bandwidth budget is applicable to the current CU. The test determines if the current CU is contained within a 512 luma sample region for which a MIP mode budget was established at the step **1220**. If the current CU is contained in a region larger than the 512 luma sample region, there is no applicable budget constraint and the CU is not subject to further constraint upon the usage of MIP mode. Control in the processor **205** progresses to the encode MIP mode flag step **1430** (“TRUE” at **1420**).

[0173] If the current CU is contained in a region equal in size or smaller than 512 luma samples, the required budget to use MIP mode for the current CU, as described with reference to FIG. **8**, is compared against the remaining budget for the region. If insufficient budget is available to apply MIP mode to the current CU, control in the processor **205** progresses from step **1420** to an encode TB step **1440** (“FALSE” at step **1420**). However, if sufficient budget is available to apply MIP

mode to the current CU (“TRUE” at **1420**), control in the processor **205** progresses from step **1420** to step **1430** even if the current CU is in a region less than or equal to 512 samples. Operation of the step **1420** corresponds with operation of the step **1330** and accordingly, a MIP flag is only encoded in the method **1400** for CUs for which MIP mode was searched in the method **1300**. [0174] At the encode MIP mode flag step **1430** the entropy encoder **338**, under execution of the processor **205**, encodes a context-coded bin indicating the selection of MIP mode or not, as determined at the step **1350**, into the bitstream **115**. The context to use for encoding the bin is described with reference to step **1420**. Where MIP mode was selected, the entropy encoder **338** also encodes the selection of which particular MIP mode is used into the bitstream **338**. The MIP mode may be encoded using a truncated binary codeword instead of using a selection between a ‘most probable mode’ and a remaining mode. Using a truncated binary codeword avoids the necessity to derive a list of most probable modes, including potential table lookups where most probable modes are derived from neighbouring angular intra predicted CUs. Control in the processor **205** progresses from the step **1430** to the encode TB step **1440**.

[0175] At the encode TB step **1440** the entropy encoder **338**, under execution of the processor **205**, encodes the residual coefficients of the TBs associated with the current CU into the bitstream. Generally, a flag for each TB signals the presence of at least one significant coefficient, the coefficients are encoded one-by-one according to a scan pattern progressing from a last significant coefficient position back to a DC (top-left) coefficient position. The method **1400** then terminates and control in the processor **205** returns to the method **1100**.

[0176] FIG. **15** shows a method **1500** for decoding coding units and transform blocks of an image frame from a video bitstream **133**. The method **1500** may be embodied by apparatus such as a configured FPGA, an ASIC, or an ASSP. Additionally, the method **1500** may be performed by the video decoder **134** under execution of the processor **205**. As such, the method **1500** may be stored on computer-readable storage medium and/or in the memory **206**. The method **1500** commences at a divide frame into CTUs step **1510**.

[0177] At the divide frame into CTUs step **1510** the video decoder **134**, under execution of the processor **205**, divides a current frame of the frame data **133** (to be decoded) into an array of CTUs. A progression of decoding over the CTUs resulting from the division commences. Control in the processor **205** progresses from the step **1510** to a decode coding unit step **1520**.

[0178] At the decode coding unit step **1520** the entropy decoder **420**, under execution of the processor **205**, decodes split flags from the bitstream **133** in accordance with the coding tree as described with reference to FIGS. **5-7**. Decoding the split flags allows the step **1520** to operate to determine the size and location of a CU within the CTU, i.e. in accordance with the coding tree of the CTU. Progression of the method **1300** involves iteration over the step **1520**, resulting in a traversal over the coding tree of the CTU, with each CU being decoded. Control in the processor **205** progresses from the step **1520** to a decode coding unit step **1530**.

[0179] At the decode coding unit step **1530** the entropy decoder **420**, under execution of the processor **205**, decodes the coding unit from the bitstream **133**. The step **1530** invokes a method **1600**, described hereafter in relation to FIG. **16**, to decode the CU. Control in the processor **205** progresses from the step **1530** to a last coding unit test step **1540**.

[0180] At the last coding unit test step **1540** the processor **205** tests if the current coding unit is the last coding unit in the CTU, as determined from decoding split flags at step **1520**. If the current coding unit is the last in the CTU (“YES” at step **1540**), control in the processor progresses to a last CTU test step **1550**. If the current coding unit is not the last one in the coding tree of step **1520** (“NO” at step **1540**), the next coding unit in the coding tree of step **1520** is selected for decoding and control in the processor **205** progresses to the step **1520**.

[0181] At the last CTU test step **1550** the processor **205** tests if the current CTU is the last CTU in the slice or frame. If the current CU is not the last (“NO” at step **1550**), the video decoder **134** advances to the next CTU in the frame or slice and control in the processor **205** progresses from the

step **1550** back to the step **1520** to continue processing remaining CTUs in the frame. If the CTU is the last one in the frame or slice, the step **1550** returns “YES” and the method **1500** terminates. As a result of the method **1500**, an entire image frame is decoded as a sequence of CTUs from a bitstream.

[0182] FIG. **16** shows the method **1600** for decoding a coding unit from a video bitstream **133**, as implemented at step **1530**. The method **1600** may be embodied by apparatus such as a configured FPGA, an ASIC, or an ASSP. Additionally, the method **1600** may be performed by video decoder **134** under execution of the processor **205**. As such, the method **1600** may be stored on computer-readable storage medium and/or in the memory **206**. The method **1600** commences at a decode pred_mode flag step **1602**.

[0183] At the decode pred_mode flag step **1602** the entropy decoder **420** decodes a context-coded bin to determine if the current coding unit uses inter prediction or intra prediction (including MIP mode). Control in the processor **205** continues from step **1602** to an inter prediction test step **1604**. The step **1604** executes to determine if inter prediction is used from the pred_mode flag. If the current coding unit uses inter prediction (“TRUE” at inter prediction test step **1604**) control in the processor **205** continues from step **1602** to a perform inter prediction step **1606**. Inter prediction is performed at step **1606**, resulting in fetching a reference block (**434**) and filtering to produce a PU, followed by decoding a TB for each colour channel and adding the TB (**1690**) to the PU to decode the CU. Control in the processor **205** continues from step **1606** to an add TB step **1690**.

[0184] If the current coding unit uses intra prediction or MIP mode (“FALSE” at step **1604**) control on the processor **205** continues to a MIP mode budget test step **1610**. The MIP mode budget test step **1610** executes to determine whether MIP mode is available for the current CU in accordance with a budget. The budget corresponds to the budget described with reference to steps **1330** or **1420**. In the example described, if the region containing the current CU is larger than the area threshold (512 luma samples), there is no applicable budget constraint and MIP mode is available (TRUE at step **1610**). Control in the processor **205** progresses from step **1610** to a decode MIP mode flag step **1620**.

[0185] If at step **1610** the region containing current CU is equal in area or smaller than the threshold (512 luma samples), the required budget to use MIP mode for the current CU, as described with reference to FIG. **8**, is compared against the remaining budget for the region. If sufficient budget is available to apply MIP mode to the current CU, MIP mode is available (“TRUE” at step **1610**) and the method **1600** continues to step **1620**. If insufficient budget is available, MIP mode is not available for the current CU (“FALSE” at MIP mode budget test step **1610**) and control in the processor **205** continues to a decode intra prediction mode step **1612**.

[0186] At step **1612** regular intra prediction (DC, planar or angular) is used, starting by decoding an intra prediction mode. Control in the processor **205** continues from step **1612** to a perform intra prediction step **1614**. and the step **1614** operates to performing intra prediction. Control in the processor **205** continues from step **1614** to the add TB step **1690**.

[0187] In execution of step **1620** a MIP flag is decoded by the entropy decoder **420** using a single context-coded bin. The bin uses one context, i.e., there is no context selection necessary, for example, depending on the usage of MIP mode for neighbouring CUs or the block size or other parameter that may be used to select one context from multiple possible contexts for decoding a single bin. Control in the processor continues from step **1620** to a MIP mode selected test step **1630**.

[0188] The step **1630** operates to determine whether MIP mode is selected. If the decoded MIP mode flag indicates MIP mode is not in use (“FALSE” at MIP mode selected test step **1630**) control proceeds to the step **1612** to decode a block using one of the regular intra prediction modes. If the decoded MIP mode flag indicates MIP mode is used for the CU (“TRUE” at step **1630**), control in the processor **205** operates to continue to a decode MIP mode step **1640**.

[0189] A MIP mode is decoded from the bitstream **133** in execution of step **1640**. Control in the

processor **205** continues from step **1640** to a read matrix coefficients step **1650**. The decoded MIP mode is used to read the set of matrix coefficients **481** from the matrix coefficient memory **486** at step **1650**. By virtue of restricting availability of using MIP mode at step **1610** through use of the budget, maximum memory bandwidth consumption required for the matrix coefficient memory **486** to supply matrix coefficients **481** is reduced.

[0190] The method **1600** continues from step **1650** to a filtering neighbouring samples step **1660**. Neighbouring reference samples **464** are filtered at step **1660**. The method **1600** continues from step **1660** to a matrix multiply step **1670**. The step **1600** can be implemented by the module **482** for example using matrix coefficients **481** and samples **464**. The filtered reference samples and the matrix coefficients **481** are multiplied at step **1670** similarly to the example **828** of FIG. **8**.

[0191] The method **1600** continues from step **1670** to an interpolate PB step **1680**. The sparse block (i.e., **830**) determined from execution of step **1670** is used to populate a PB (i.e. **483**) with an interpolation operation at step **1680**. The method **1600** continues from step **1680** to an interpolate PB the add TB step **1690**. A decoded residual is used to generate a TB, which is added to the PB **483** at step **1690** to decode the CU. The coding units are decoded using the prediction blocks generated at step **1690**. The method **1600** terminates upon completion of the step **1690**.

[0192] The video decoder **134**, in performing the method **1600**, achieves support of matrix intra prediction with a constraint upon worst case memory bandwidth for fetching matrix coefficients. The constraint described does not overly restrict selection of the MIP mode in terms of affecting error compared to a case where no usage restriction is in effect. Operation that does not overly restrict selection is due to a determined statistical likelihood of generally only 20% of MIP mode-coded CUs have a left or above neighbour that also uses MIP mode. Boundaries across regions larger than the regions used as the granularity for establishing a memory access budget, i.e., 512 luma samples and boundaries across CTUs included in measurement of the 20% finding.

[0193] In the example implementation of FIGS. **11-16**, whether MIP mode is used in based on a constraint. The constraint is implemented based on whether the area of the region of the current CU and whether matrix intra prediction flags are encoded or decoded depends on whether the area of the region of the current CU satisfies the threshold area, e.g. at FIG. **12**. In the implementation described, whether matrix intra prediction flags are encoded depends on an area of the region if the region meets a threshold, or (ii) a budget for the region if the area of the region does not meet the threshold as described in relation to steps **1330**, **1420** and **1610**. Accordingly, whether matrix intra prediction flags are encoded (or decoded) depends at least on whether the area of the region satisfies the threshold area.

[0194] In the implementation described in FIGS. **11-14** a MIP mode flag is only encoded in the bitstream **115** if the budget test is satisfied, as described in relation to steps **1420** and **1430**.

Correspondingly, in decoding the bitstream at FIG. **16** a MIP mode flag is only decoded if the MIP mode budget test step returns TRUE. In other words, matrix intra prediction flags are decoded for the CU only if matrix intra prediction is used.

[0195] In an alternative arrangement of the video encoder **114** and the video decoder **134** searching of the MIP mode is restricted, as described with reference to FIGS. **12** and **13**. However, in the alternative arrangement, signalling of the MIP flag is included in the bitstream for each CU, regardless of the status of budget consumption for each CU. In other words, matrix intra prediction flags are decoded for the CU regardless of whether matrix intra prediction is used. In the alternative arrangement, step **1420** is omitted and control progresses to the step **1430** (“TRUE” at step **1420**) in the video encoder **114**, as indicated using an arrow **1411** shown in broken lines in FIG. **14**. A MIP mode flag is included in all cases at step **1430** in the alternative arrangement but can be set to zero if MIP mode was not selected at step **1350**. Likewise, in the video decoder **134** the step **1610** is omitted and control progresses to the step **1620** (effectively “TRUE” is always returned at step **1610**). The MIP mode flag is decoded at step **1620** and is zero if MIP mode was not selected at step **1350** of encoding the bitstream. The additional burden in the entropy encoder **338** and the entropy

decoder **420** of decoding whether or not to code a MIP flag for each CU is avoided. Notwithstanding that the bitstream now includes the MIP mode flag for each CU, the searching as performed in the methods **1200** and **1300** ensures that the memory bandwidth for reading the matrix coefficients **481** from the coefficient memory **486** in the video decoder **134** is still restricted, reducing the necessary provisioning of resources for handling this (constrained) worst case usage of MIP mode.

[0196] The implementation described in relation to FIGS. **12-17** above apply a constraint for use of MIP mode based on area of a region containing a CU. In yet a further arrangement of the video encoder **114** and the video decoder **134**, the constraint implemented at FIG. **12** prohibits usage of matrix intra prediction for block sizes corresponding to the worst case memory bandwidth rather than based on area of a region. Effectively, matrix intra prediction is used (and matrix intra prediction flags encoded or decoded) based on a size of each coding block. Block sizes of 4×4 , 4×8 , 8×4 , 8×8 , 8×16 , and 16×8 result in the highest access density (for example, as measured with respect to 4×4 luma sample blocks) of 80 words per 4×4 block. Certain block sizes among the preceding set of block sizes have a worst case of 72 words per 4×4 block, however for the purposes of resource provisioning this may be treated in the same category as the 80 words per 4×4 block cases. Prohibition of the worst case block sizes establishes a worst case of 40 words per 4×4 block (with certain block sizes having a worst case of 36 words per 4×4 block).

[0197] FIG. **17** shows a method **1700** for determining a coding unit as implemented at step **1130**. The method **1300** provides an alternative to the method **1300** for implementations where the constraint relates to prohibiting usage of matrix intra prediction for block sizes corresponding to the worst case memory bandwidth. The method **1700** involves determining a prediction mode for a coding unit as generated by performing the method **1200**. The prediction mode includes intra prediction, inter prediction and MIP mode according to allowability use of MIP mode within a region containing the current coding unit. The method **1700** commences at a test intra prediction modes step **1710**.

[0198] At the test intra prediction modes step **1310** the video encoder **114**, under execution of the processor **205**, tests ‘regular’ intra prediction modes, i.e. DC, planar, and angular intra prediction modes, for potential use in coding the current coding unit and operates in the manner described for step **1310**. Control in the processor **205** progresses from the step **1710** to a test inter prediction modes step **1720**.

[0199] At the test inter prediction modes step **1720** the video encoder **114**, under execution of the processor **205**, tests various motion vectors for generating inter predicted PUs. When evaluating use of inter prediction, a motion vector is selected from a set of candidate motion vectors. The step **1720** operates in the same manner as step **1320**. Control in the processor **205** progresses from the step **1720** to MIP allowable size test step **1730**.

[0200] At the MIP allowable size test step **1730** the video encoder **114**, under execution of the processor **205**, tests if the CU is of a size where MIP mode is allowable. MIP mode is allowable for all sizes except the worst case sizes 4×4 , 4×8 , 8×4 , 8×8 , 8×16 and 16×8 in some implementations. If the current CU is an allowable size (“TRUE” at **1730**) control in the processor **205** progresses from step **1730** to a test MIP modes step **1740**. If the current CU is a prohibited size (“FALSE” at step **1730**) control in the processor **205** progresses from step **1730** to a select mode step **1750**.

[0201] At the test MIP modes step **1740** the mode selector **386** tests various MIP modes to determine a best MIP mode for use for predicting the current CU, among the available MIP modes for the size of the CU. The step **1740** operates in the same manner as the step **1340** in the processor **205** progresses from the step **1740** to a select mode step **1750**.

[0202] At the select mode step **1750** the mode selector **386**, under execution of the processor **205**, selects a final mode for the CU from the candidates resulting from the steps **1710**, **1720**, and **1750**. The method **1700** terminates with control in the processor **205** returning to the method **1100**.

[0203] FIG. **18** shows a method **1800** for encoding a coding unit of a coding tree of a CTU into the

video bitstream **115**, as implemented at step **1140** in implementations where the constraint relates to prohibiting usage of matrix intra prediction for block sizes corresponding to the worst case memory bandwidth. The method **1800** may be embodied by apparatus such as a configured FPGA, an ASIC, or an ASSP. Additionally, the method **1800** may be performed by video encoder **114** under execution of the processor **205**. As such, the method **1800** may be stored on computer-readable storage medium and/or in the memory **206**. The method **1800** commences at an encode prediction mode step **1810**.

[0204] At the encode prediction mode step **1810** the entropy encoder **338**, under execution of the processor **205**, encodes a flag using a context coded bin indicating the use of either intra prediction (including both regular intra prediction mode use or MIP mode use) or inter prediction, as determined at the step **1750**. Control in the processor **205** progresses from the step **1810** to a MIP allowable size test step **1820**.

[0205] At the MIP allowable size test step **1820** the video encoder **114**, under execution of the processor **205**, tests if the current CU is an allowable size or not. The allowable sizes and the prohibited sizes are the same as for the step **1730** of the method **1700**. If the current CU is an allowable size control in the processor **205** progresses to an encode MIP mode flag step **1830** (“TRUE” at **1820**).

[0206] If the current CU not an allowable size (“FALSE” at step **1820**), control in the processor **205** progresses from step **1820** to an encode TB step **1840**.

[0207] At the encode MIP mode flag step **1830** the entropy encoder **338**, under execution of the processor **205**, encodes a context-coded bin indicating the selection of MIP mode or not, as determined at the step **1350**, into the bitstream **115**. The step **1830** operates in the same manner as the step **1430**. Control in the processor **205** progresses from the step **1830** to the encode TB step **1840**.

[0208] At the encode TB step **1840** the entropy encoder **338**, under execution of the processor **205**, encodes the residual coefficients of the TBs associated with the current CU into the bitstream. The step **1840** operates in a similar manner to the step **1440**. The method **1800** then terminates and control in the processor **205** returns to the method **1100**.

[0209] FIG. **19** shows the method **1900** for decoding a coding unit from a video bitstream **133**, as implemented at step **1530** for implementations where the constraint relates to prohibiting MIP mode for worst case blocks. The method **1900** may be embodied by apparatus such as a configured FPGA, an ASIC, or an ASSP. Additionally, the method **1900** may be performed by video decoder **134** under execution of the processor **205**. As such, the method **1900** may be stored on computer-readable storage medium and/or in the memory **206**. The method **1900** commences at a decode pred_mode flag step **1902**.

[0210] At the decode pred_mode flag step **1902** the entropy decoder **420** decodes a context-coded bin to determine if the current coding unit uses inter prediction or intra prediction (including MIP mode). If the current coding unit uses inter prediction (“TRUE” at inter prediction test step **1904**) control in the processor continues to a perform inter prediction step **1906**. Inter prediction is performed at step **1606**, resulting in fetching a reference block (**434**) and filtering to produce a PU, followed by decoding a TB for each colour channel and adding the TB (**1690**) to the PU to decode the CU. Similarly, control in the processor **205** continues from step **1906** to an add TB step **1990**.

[0211] If the current coding unit uses intra prediction or MIP mode (“FALSE” at step **1904**) control on the processor **205** continues to a MIP allowable size test step **1910**. MIP allowable size test step **1910** executes to determine whether MIP mode is allowable for the current CU size. The MIP allowable sizes are described with reference to steps **1730** or **1820**. If the current CU is an allowable size (TRUE at step **1910**), control in the processor **205** progresses from step **1910** to a decode MIP mode flag step **1920**. If at step **1910** the current CU is not an allowable size (“FALSE” at step **1910**) and control in the processor **205** continues to a decode intra prediction mode step **1912**.

[0212] At step **1912** a regular intra prediction (DC, planar or angular) is decoded and the method **1900** continues to a decode intra prediction step **1914**. The steps **1912** and **1914** operate the manner described in relation to steps **1612** and **1614**. Control in the processor **205** continues from step **1914** to the add TB step **1990**.

[0213] In execution of step **1920** a MIP flag is decoded. Control in the processor **205** continues from step **1920** to a MIP mode selected test step **1930**.

[0214] The step **1930** operates to determine whether MIP mode is selected. If the decoded MIP mode flag indicates MIP mode is not in use (“FALSE” at MIP mode selected test step **1930**) control proceeds to the step **1912** to decode a block using one of the regular intra prediction modes. If the decoded MIP mode flag indicates MIP mode is used for the CU (“TRUE” at step **1930**), control in the processor operates to continue to a decode MIP mode step **1940**.

[0215] A MIP mode is decoded from the bitstream **133** in execution of step **1940**. Control in the processor **205** continues from step **1940** to a read matrix coefficients step **1950**. The decoded MIP mode is used to read the set of matrix coefficients **481** from the matrix coefficient memory **486** at step **1950**. Matrix coefficients are read for each prediction block determined to use MIP mode, as at step **1650**.

[0216] The method **1900** continues from step **1950** to a filtering neighbouring samples step **1660**. Neighbouring reference samples **464** are filtered at step **1960**. The method **1900** continues from step **1960** to a matrix multiply step **1970**. The filtered reference samples and the matrix coefficients **481** are multiplied at step **1970** similarly to the example **828** of FIG. **8**.

[0217] The method **1900** continues from step **1970** to an interpolate PB step **1980**. The sparse block (i.e., **830**) determined from execution of step **1970** is used to populate a PB (i.e. **483**) with an interpolation operation at step **1980**. The method **1900** continues from step **1980** to an interpolate PB the add TB step **1990**. A decoded residual is used to generate a TB, which is added to the PB **483** at step **1990** to decode the CU, similarly to step **1690**. The method **1900** terminates upon completion of the step **1990**.

[0218] Modifications described to the methods **1300**, **1400** and **1600** can also be applied to the methods **1700**, **1800** and **1900** respectively.

[0219] When block size is used as the criteria for availability of the MIP mode, as in the method **1700**, there is no need to establish and update a memory budget, i.e. steps **1210** and **1220** are omitted. Removal of MIP mode for certain block sizes, although simpler to implement than budgeting memory accesses, results in lower compression performance due to the absence of the MIP mode from a number of popular block sizes. The coefficient memory (i.e., **392**, **486**) is reduced in size as the absence of 4×4 blocks means that no matrix coefficients of ‘Set A’ (18 sets of matrix coefficients and bias values) need to be stored. Removal of the MIP mode from 4×4, 4×8, 8×4, 8×8, 8×16, and 16×8 (“small blocks”) also has an advantage in that the feedback loop of the MIP mode, which is a relatively complex operation, does not need to support these small blocks.

[0220] In yet another arrangement, usage of the MIP mode is prohibited for a subset of the small blocks (as listed above). For example, MIP mode is prohibited only for 4×4 blocks at steps **1730**, **1820** and **1910** but allowed for all other block sizes or MIP mode is prohibited for 4×4, 4×8, and 8×4 blocks but allowed for all other block sizes. In other words, matrix intra prediction is not used and, depending on the implementation, matrix intra prediction flags are decoded if the size of the coding unit is one of the prohibited sizes. Worst case memory bandwidth is not reduced compared to a complete lack of restriction on usage of the MIP mode but the severity of the intra reconstruction feedback loop is lessened due to the exclusion of these very small block sizes.

Removal of 4×4 also removes the need to store matrix coefficients associated with “Set A” from the coefficient memory (i.e. **392**, **486**). Alternatively, prohibited set of block sizes may be 4×4, 4×8, 8×4, and 8×8, in which case Sets A and B are not present in the video encoder **114** or the video decoder **134**. Removal of Sets A and B results in reduced memory consumption as the matrix coefficients associated with Sets A and B are not needed, at the expense of reduced compression

performance.

[0221] In yet another arrangement, the memory budget is lower still than 40 words per 4×4 luma sample area, for example 20 or even 10 words per 4×4 luma sample area. The budget is established over a larger region size, such as at nodes corresponding to a region size of 1024 or 2048 luma samples. As with the arrangements described above, later CUs within the restricted are constrained in the availability of memory budget according to the usage of the MIP mode for earlier CUs within these regions. Further reduction in memory bandwidth is achieved at the expense of lower compression efficiency.

[0222] In yet another arrangement, the memory budget is established at the region size of 64 luma samples at steps **1220**, **1330**, **1420** and **1610** for application to CUs of sizes 4×4 , 4×8 , and 8×4 (a “small CU memory budget”). A separate memory budget is established at the region size of 512 but only applicable to CUs of sizes exceeding 8×8 , in particular 8×16 and 16×8 (a “larger CU memory budget”). Both budgets are set at 40 words per 4×4 luma sample area. The budgets form an additive budget to the total matrix memory bandwidth because the small CU memory budget applies only to CUs contained within 64 luma sample areas whereas the larger CU memory budget applies only to CUs larger than 64 luma samples.

[0223] Although arrangements disclosed herein describe memory bandwidth in terms of words per 4×4 memory region, it is understood that accesses to memory are likely to group words in some SIMD form to allow reading the matrix coefficients without requiring excessive clock frequency of the associated memory. Nevertheless, such wider memories are themselves costly and the matrix coefficients may be shared with other data in the same memory, resulting in access contention that is reduced by restrictions on usage of the MIP mode.

[0224] Restricting usage of MIP mode to limit worst-case memory bandwidth on a region-by-region basis may introduce a bias towards CUs earlier (closer to the top or left) of each region to use MIP mode whereas CUs later in a given region are unable to use MIP mode as the available budget for the region was consumed by earlier encountered CUs. Such a bias is not normally encountered as the distribution of CUs for which MIP mode is selected is generally somewhat sparse.

[0225] The arrangements described implements constraints on when MIP mode may be used, thereby reducing computational complexity compared to allowing implementation of MIP mode without constraint. The reduced complexity is achieved without a proportionate degradation in coding efficiency because the statistics of MIP mode selection in an unconstrained search do not usually trigger the constraints imposed upon the MIP mode selection in the mode selector **386**. Thus, worst case memory bandwidth is reduced without a commensurate loss in coding performance.

INDUSTRIAL APPLICABILITY

[0226] The arrangements described are applicable to the computer and data processing industries and particularly for the digital signal processing for the encoding a decoding of signals such as video and image signals, achieving high compression efficiency.

[0227] The arrangements described herein permit residual encoding and decoding to use a trellis-based state machine that updates according to coefficient parity and selects contexts and quantisers for coefficients. The arrangements described allow implementation of the trellis-based state machine without imposing excessive latency due to the sequential nature of the state update.

[0228] The foregoing describes only some embodiments of the present invention, and modifications and/or changes can be made thereto without departing from the scope and spirit of the invention, the embodiments being illustrative and not restrictive.

Claims

1. A method of generating prediction samples for a target block in a coding tree unit for an image frame, the method comprising: decoding a matrix intra prediction flag for the target block, the matrix intra prediction flag indicating whether matrix intra prediction is used for the target block; in a case where the matrix intra prediction flag indicates matrix intra prediction is used for the target block, decoding a matrix intra prediction mode for the target block, wherein a truncated binary code can be used for the matrix intra prediction mode; selecting, according to the matrix intra prediction mode, a matrix for matrix intra prediction for the target block; and generating the prediction samples by applying a multiplication of input samples based on samples neighbouring the target block and the matrix selected according to the matrix intra prediction mode, wherein the samples neighboring the target block include those to the left of the target block, wherein in a case where a given area in the coding tree unit is split into four blocks each having a size of 16×8 and the target block is one of the four blocks, decoding of the matrix intra prediction flag for the target block depends on a state of use of matrix intra prediction of two blocks adjacent to the target block, wherein in a case where a size of the target block is one of a size of 8×16 and a size of 16×8 , (a) the matrix intra prediction mode is one of matrix intra prediction modes available for the size of 8×16 and the size of 16×8 , (b) the number of the matrix intra prediction modes available for the size of 8×16 and the size of 16×8 is n (n is an integer value greater than 0), (c) the matrix intra prediction mode is represented by an integer value which is equal to or greater than 0 and is equal to or less than $n-1$, (d) a code of m -bits (m is an integer number greater than 0) is used for the matrix intra prediction mode represented by an integer value which is equal to or greater than 0 and equal to or less than a predetermined integer value, or (e) a code of $m+1$ -bits is used for matrix intra prediction mode represented by an integer value which is greater than the predetermined integer value and is equal to or less than $n-1$.
2. The method according to claim 1, wherein n is an integer value which is greater than 2 to the power of m and is less than 2 to the power of $m+1$.
3. A method of generating prediction samples for a target block in a coding tree unit for an image frame, the method comprising: selecting a matrix for matrix intra prediction for the target block; generating the prediction samples by applying a multiplication of input samples based on samples neighbouring the target block and the selected matrix; wherein the samples neighboring the target block include those to the left of the target block, encoding a matrix intra prediction flag for the target block, the matrix intra prediction flag indicating whether matrix intra prediction is used for the target block; and in a case where matrix intra prediction is used for the target block, encoding a matrix intra prediction mode which indicates the selected matrix, wherein a truncated binary code can be used for the matrix intra prediction mode, wherein in a case where a given area in the coding tree unit is split into four blocks each having a size of 16×8 and the target block is one of the four blocks, encoding of the matrix intra prediction flag for the target block depends on a state of use of matrix intra prediction of two blocks adjacent to the target block, wherein in a case where a size of the block is one of a size of 8×16 and a size of 16×8 , (a) the matrix intra prediction mode is one of matrix intra prediction modes available for the size of 8×16 and the size of 16×8 , (b) the number of the matrix intra prediction modes available for the size of 8×16 and the size of 16×8 is n (n is an integer value greater than 0), (c) the matrix intra prediction mode is represented by an integer value which is equal to or greater than 0 and is equal to or less than $n-1$, (d) a code of m -bits (m is an integer number greater than 0) is used for the matrix intra prediction mode represented by an integer value which is equal to or greater than 0 and equal to or less than a predetermined integer value, or (e) a code of $m+1$ -bits is used for the matrix intra prediction mode represented by an integer value which is greater than the predetermined integer value and is equal to or less than $n-1$.
4. The method according to claim 3, wherein n is greater than 2 to the power of m and is less than 2 to the power of $m+1$.
5. An apparatus for generating prediction samples for a target block in a coding tree unit for an

image frame, the apparatus comprising: a first decoding unit configured to decode a matrix intra prediction flag for the target block, the matrix intra prediction flag indicating whether matrix intra prediction is used for the target block; a second decoding unit configured to decode a matrix intra prediction mode for the target block, in a case where the matrix intra prediction flag indicates matrix intra prediction is used for the target block, wherein a truncated binary code can be used for the matrix intra prediction mode; a selecting unit configured to select, according to the matrix intra prediction mode, a matrix for matrix intra prediction for the target block; and a generating unit configured to generate the prediction samples by applying a multiplication of input samples based on samples neighbouring the target block and the matrix selected according to the matrix intra prediction mode, wherein the samples neighboring the target block include those to the left of the target block, wherein in a case where a given area in the coding tree unit is split into four blocks each having a size of 16×8 and the target block is one of the four blocks, decoding of the matrix intra prediction flag for the target block depends on a state of use of matrix intra prediction of two blocks adjacent to the target block, wherein in a case where a size of the target block is one of a size of 8×16 and a size of 16×8 , (a) the matrix intra prediction mode is one of matrix intra prediction modes available for the size of 8×16 and the size of 16×8 , (b) the number of the matrix intra prediction modes available for the size of 8×16 and the size of 16×8 is n (n is an integer value greater than 0), (c) the matrix intra prediction mode is represented by an integer value which is equal to or greater than 0 and is equal to or less than $n-1$, (d) a code of m -bits (m is an integer number greater than 0) is used for the matrix intra prediction mode represented by an integer value which is equal to or greater than 0 and equal to or less than a predetermined integer value, or (e) a code of $m+1$ -bits is used for matrix intra prediction mode represented by an integer value which is greater than the predetermined integer value and is equal to or less than $n-1$.

6. An apparatus for generating prediction samples for a target block in a coding tree unit for an image frame, the apparatus comprising: a selecting unit configured to select a matrix for matrix intra prediction for the target block; a generating unit configured to generate the prediction samples by applying a multiplication of input samples based on samples neighbouring the target block and the selected matrix; wherein the samples neighboring the target block include those to the left of the target block, a first encoding unit configured to encode a matrix intra prediction flag for the target block, the matrix intra prediction flag indicating whether matrix intra prediction is used for the target block; and a second encoding unit configured to encode a matrix intra prediction mode which indicates the selected matrix, in a case where matrix intra prediction is used for the target block, wherein a truncated binary code can be used for the matrix intra prediction mode, wherein in a case where a given area in the coding tree unit is split into four blocks each having a size of 16×8 and the target block is one of the four blocks, encoding of the matrix intra prediction flag for the target block depends on a state of use of matrix intra prediction of two blocks adjacent to the target block, wherein in a case where a size of the block is one of a size of 8×16 and a size of 16×8 , (a) the matrix intra prediction mode is one of matrix intra prediction modes available for the size of 8×16 and the size of 16×8 , (b) the number of the matrix intra prediction modes available for the size of 8×16 and the size of 16×8 is n (n is an integer value greater than 0), (c) the matrix intra prediction mode is represented by an integer value which is equal to or greater than 0 and is equal to or less than $n-1$, (d) a code of m -bits (m is an integer number greater than 0) is used for the matrix intra prediction mode represented by an integer value which is equal to or greater than 0 and equal to or less than a predetermined integer value, or (e) a code of $m+1$ -bits is used for the matrix intra prediction mode represented by an integer value which is greater than the predetermined integer value and is equal to or less than $n-1$.

7. A non-transitory computer-readable storage medium storing a program for causing a computer to execute a method of generating prediction samples for a target block in a coding tree unit for an image frame, the method comprising: decoding a matrix intra prediction flag for the target block, the matrix intra prediction flag indicating whether matrix intra prediction is used for the target

block; in a case where the matrix intra prediction flag indicates matrix intra prediction is used for the target block, decoding a matrix intra prediction mode for the target block, wherein a truncated binary code can be used for the matrix intra prediction mode; and selecting, according to the matrix intra prediction mode, a matrix for matrix intra prediction for the target block; and generating the prediction samples by applying a multiplication of input samples based on samples neighbouring the target block and the matrix selected according to the matrix intra prediction mode, wherein the samples neighboring the target block include those to the left of the target block, wherein in a case where a given area in the coding tree unit is split into four blocks each having a size of 16×8 and the target block is one of the four blocks, decoding of the matrix intra prediction flag for the target block depends on a state of use of matrix intra prediction of two blocks adjacent to the target block, wherein in a case where a size of the target block is one of a size of 8×16 and a size of 16×8 , (a) the matrix intra prediction mode is one of matrix intra prediction modes available for the size of 8×16 and the size of 16×8 , (b) the number of the matrix intra prediction modes available for the size of 8×16 and the size of 16×8 is n (n is an integer value greater than 0), (c) the matrix intra prediction mode is represented by an integer value which is equal to or greater than 0 and is equal to or less than $n-1$, (d) a code of m -bits (m is an integer number greater than 0) is used for the matrix intra prediction mode represented by an integer value which is equal to or greater than 0 and equal to or less than a predetermined integer value, or (e) a code of $m+1$ -bits is used for matrix intra prediction mode represented by an integer value which is greater than the predetermined integer value and is equal to or less than $n-1$.

8. A non-transitory computer-readable storage medium storing a program for causing a computer to execute a method of generating prediction samples for a target block in a coding tree unit for an image frame, the method comprising: selecting a matrix for matrix intra prediction for the target block; generating the prediction samples by applying a multiplication of input samples based on samples neighbouring the target block and the selected matrix; wherein the samples neighboring the target block include those to the left of the target block, encoding a matrix intra prediction flag for the target block, the matrix intra prediction flag indicating whether matrix intra prediction is used for the target block; and in a case where matrix intra prediction is used for the target block, encoding a matrix intra prediction mode which indicates the selected matrix, wherein a truncated binary code can be used for the matrix intra prediction mode, wherein in a case where a given area in the coding tree unit is split into four blocks each having a size of 16×8 and the target block is one of the four blocks, encoding of the matrix intra prediction flag for the target block depends on a state of use of matrix intra prediction of two blocks adjacent to the target block, wherein in a case where a size of the block is one of a size of 8×16 and a size of 16×8 , (a) the matrix intra prediction mode is one of matrix intra prediction modes available for the size of 8×16 and the size of 16×8 , (b) the number of the matrix intra prediction modes available for the size of 8×16 and the size of 16×8 is n (n is an integer value greater than 0), (c) the matrix intra prediction mode is represented by an integer value which is equal to or greater than 0 and is equal to or less than $n-1$, (d) a code of m -bits (m is an integer number greater than 0) is used for the matrix intra prediction mode represented by an integer value which is equal to or greater than 0 and equal to or less than a predetermined integer value, or (e) a code of $m+1$ -bits is used for the matrix intra prediction mode represented by an integer value which is greater than the predetermined integer value and is equal to or less than $n-1$.
