The coding order for hierarchical prediction structures has to be chosen in a way that reference pictures are coded before they are employed for motion-compensated prediction. This can be ensured by different strategies, which mostly differ in the associated decoding delay and memory requirement. For a detailed analysis, the reader is referred to [28] and [29].

The coding efficiency for hierarchical prediction structures is highly dependent on how the quantization parameters are chosen for pictures of different temporal layers. Intuitively, the pictures of the temporal base layer should be coded with highest fidelity, since they are directly or indirectly used as references for motion-compensated prediction of pictures of all temporal layers. For the next temporal layer a larger quantization parameter should be chosen, since the quality of these pictures influences fewer pictures. Following this rule, the quantization parameter should be increased for each subsequent hierarchy level. Additionally, the optimal quantization parameter also depends on the local signal characteristics.

An improved selection of the quantization parameters can be achieved by a computationally expensive rate-distortion analysis similar to the strategy presented in [30]. In order to avoid such a complex operation, we have chosen the following strategy (cp. [31]), which proved to be sufficiently robust for a wide range of tested sequences. Based on a given quantization parameter QP_0 for pictures of the temporal base layer, the quantization parameters for enhancement layer pictures of a given temporal layer with an identifier $T > 0$ are determined by $QP_T = QP_0 + 3 + T$. Although this strategy for cascading the quantization parameters over hierarchy levels results in relatively large peak SNR (PSNR) fluctuations inside a group of pictures, subjectively, the reconstructed video appears to be temporally smooth without annoying temporal "pumping" artifacts.

Often, motion vectors for bipredicted blocks are determined by independent motion searches for both reference lists. It is, however, well-known that the coding efficiency for B-slices can be improved when the combined prediction signal (weighted sum of list 0 and list 1 predictions) is considered during the motion search, e.g., by employing the iterative algorithm presented in [32].

When using hierarchical B-pictures with more than 2 temporal layers, it is also recommended to use the "spatial direct mode" of the H.264/AVC inter-picture prediction design [6], since with the "temporal direct mode" unsuitable "direct motion vectors" are derived for about half of the B-pictures. It is also possible to select between the spatial and temporal direct mode on a picture basis.

2) Coding Efficiency of Hierarchical Prediction Structures: We now analyze the coding efficiency of dyadic hierarchical prediction structures for both high- and low-delay coding. The encodings were operated according to the Joint Scalable Video Model (JSVM) algorithm [31]. The sequences were encoded using the High Profile of H.264/AVC, and CABAC was selected as entropy coding method. The number of active reference pictures in each list was set to 1 picture.

In a first experiment we analyze coding efficiency for hierarchical B-pictures without applying any delay constraint. Fig. 2 shows a representative result for the sequence "Foreman" in CIF

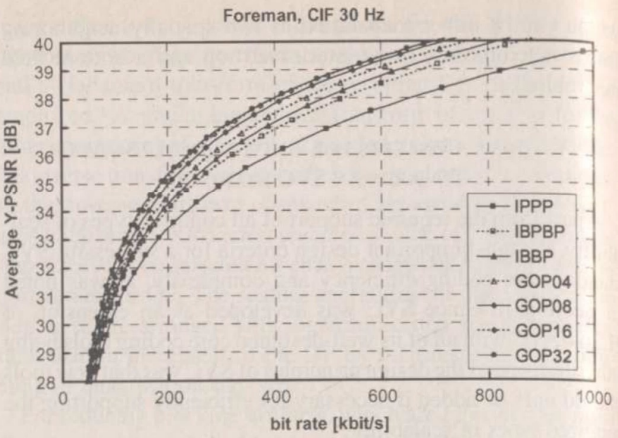


Fig. 2. Coding efficiency comparison of hierarchical B-pictures without any delay constraints and conventional IPPP, IBPBP, and IBBP coding structures for the sequence "Foreman" in CIF resolution and a frame rate of 30 Hz.

(352×288) resolution and a frame rate of 30 Hz. The coding efficiency can be continuously improved by enlarging the GOP size up to about 1 s. In comparison to the widely used IBBP coding structure, PSNR gains of more than 1 dB can be obtained for medium bit rates in this way. For the sequences of the high-delay test set (see Table I) in CIF resolution and a frame rate of 30 Hz, the bit rate savings at an acceptable video quality of 34 dB that are obtained by using hierarchical prediction structures in comparison to IPPP coding are summarized in Fig. 3(a). For all test sequences, the coding efficiency can be improved by increasing the GOP size and thus the encoding/decoding delay; the maximum coding efficiency is achieved for GOP sizes between 8 and 32 pictures.

In a further experiment the structural encoding/decoding delay is constrained to be equal to zero and the coding efficiency of hierarchical prediction structures is analyzed for the video conferencing sequences of the low-delay test set (see Table II) with a resolution of 368×288 samples and with a frame rate of 25 Hz or 30 Hz. The bit rate savings in comparison to IPPP coding, which is commonly used in low-delay applications, for an acceptable video quality of 38 dB are summarized in Fig. 3(b). In comparison to hierarchical coding without any delay constraint the coding efficiency improvements are significantly smaller. However, for most of the sequences we still observe coding efficiency gains relative to IPPP coding. From these experiments, it can be deduced that providing temporal scalability usually does not have any negative impact on coding efficiency. Minor losses in coding efficiency are possible when the application requires low delay. However, especially when a higher delay can be tolerated, the usage of hierarchical prediction structures not only provides temporal scalability, but also significantly improves coding efficiency.

B. Spatial Scalability

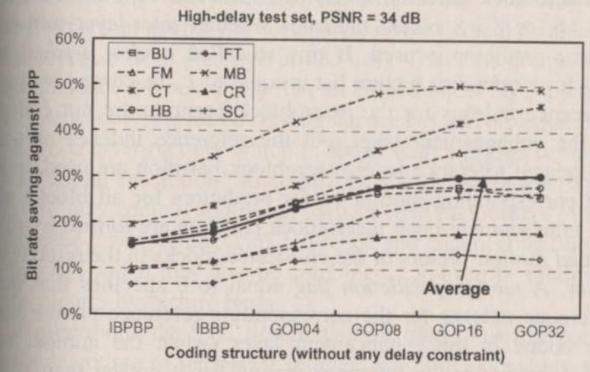
For supporting spatial scalable coding, SVC follows the conventional approach of multilayer coding, which is also used in H.262 | MPEG-2 Video, H.263, and MPEG-4 Visual. Each layer corresponds to a supported spatial resolution and is referred to by a spatial layer or *dependency identifier D*. The dependency identifier D for the base layer is equal to 0, and it is increased

TABLE I
HIGH-DELAY TEST SET

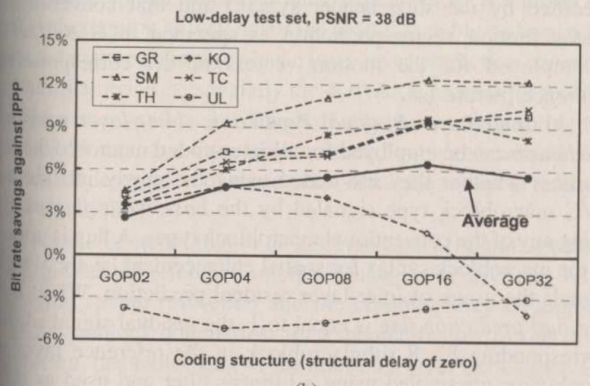
sequence name	abbre-viation	maximum resolution	maximum frame rate	number of pictures
Bus	BU	352x288	30	150
Football	FT	352x288	30	260
Foreman	FM	352x288	30	300
Mobile	MB	352x288	30	300
City	CT	704x576	60	600
Crew	CR	704x576	60	600
Harbour	HB	704x576	60	600
Soccer	SC	704x576	60	600

TABLE II
LOW-DELAY TEST SET

sequence name	abbre-viation	maximum resolution	maximum frame rate	number of pictures
Group	GR	768x576	30	300
Karsten & Oliver	KO	768x576	30	300
Stefan & Martin	SM	768x576	30	300
Tobias & Cornelius	TC	768x576	30	300
Thomas	TH	768x576	30	300
Uli	UL	768x576	25	250



(a)



(b)

Fig. 3. Bit-rate savings for various hierarchical prediction structures relative to IPPP coding. (a) Simulations without any delay constraint for the high-delay test set (see Table I). (b) Simulations with a structural delay of zero for the low-delay test set (see Table II).

by 1 from one spatial layer to the next. In each spatial layer, motion-compensated prediction and intra-prediction are employed as for single-layer coding. But in order to improve coding efficiency in comparison to simulcasting different spatial resolutions, additional so-called *inter-layer prediction* mechanisms are incorporated as illustrated in Fig. 4.

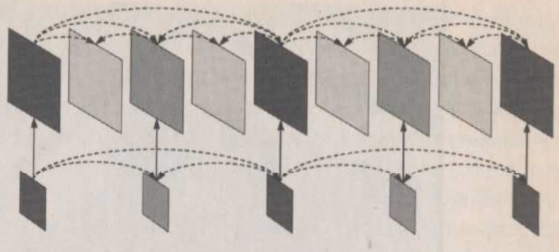


Fig. 4. Multilayer structure with additional inter-layer prediction for enabling spatial scalable coding.

In order to restrict the memory requirements and decoder complexity, SVC specifies that the same coding order is used for all supported spatial layers. The representations with different spatial resolutions for a given time instant form an access unit and have to be transmitted successively in increasing order of their corresponding spatial layer identifiers D. But as illustrated in Fig. 4, lower layer pictures do not need to be present in all access units, which makes it possible to combine temporal and spatial scalability.

1) Inter-Layer Prediction: The main goal when designing inter-layer prediction tools is to enable the usage of as much lower layer information as possible for improving rate-distortion efficiency of the enhancement layers. In H.262 | MPEG-2 Video, H.263, and MPEG-4 Visual, the only supported inter-layer prediction methods employs the reconstructed samples of the lower layer signal. The prediction signal is either formed by motion-compensated prediction inside the enhancement layer, by upsampling the reconstructed lower layer signal, or by averaging such an upsampled signal with a temporal prediction signal.

Although the reconstructed lower layer samples represent the complete lower layer information, they are not necessarily the most suitable data that can be used for inter-layer prediction. Usually, the inter-layer predictor has to compete with the temporal predictor, and especially for sequences with slow motion and high spatial detail, the temporal prediction signal mostly represents a better approximation of the original signal than the upsampled lower layer reconstruction. In order to improve the coding efficiency for spatial scalable coding, two additional inter-layer prediction concepts [33] have been added in SVC: *prediction of macroblock modes and associated motion parameters* and *prediction of the residual signal*.

When neglecting the minor syntax overhead for spatial enhancement layers, the coding efficiency of spatial scalable coding should never become worse than that of simulcast, since in SVC, all inter-layer prediction mechanisms are switchable. An SVC conforming encoder can freely choose between intra- and inter-layer prediction based on the given local signal characteristics. Inter-layer prediction can only take place inside a given access unit using a layer with a spatial layer identifier D less than the spatial layer identifier of the layer to be predicted. The layer that is employed for inter-layer prediction is also referred to as *reference layer*, and it is signaled in the slice header of the enhancement layer slices. Since the SVC



Fig. 5. Visual example for the enhancement layer when filtering across residual block boundaries (left) and omitting filtering across residual block boundaries (right) for residual prediction.

inter-layer prediction concepts include techniques for motion as well as residual prediction, an encoder should align the temporal prediction structures of all spatial layers.

Although the SVC design supports spatial scalability with arbitrary resolution ratios [34], [35], for the sake of simplicity, we restrict our following description of the inter-layer prediction techniques to the case of dyadic spatial scalability, which is characterized by a doubling of the picture width and height from one layer to the next. Extensions of these concepts will be briefly summarized in Section V-B.2.

a) Inter-Layer Motion Prediction: For spatial enhancement layers, SVC includes a new macroblock type, which is signaled by a syntax element called *base mode flag*. For this macroblock type, only a residual signal but no additional side information such as intra-prediction modes or motion parameters is transmitted. When *base mode flag* is equal to 1 and the corresponding 8×8 block[3] in the reference layer lies inside an intra-coded macroblock, the macroblock is predicted by *inter-layer intra-prediction* as will be explained in Section V-B.1c. When the reference layer macroblock is inter-coded, the enhancement layer macroblock is also inter-coded. In that case, the partitioning data of the enhancement layer macroblock together with the associated reference indexes and motion vectors are derived from the corresponding data of the co-located 8×8 block in the reference layer by so-called *inter-layer motion prediction*.

The macroblock partitioning is obtained by upsampling the corresponding partitioning of the co-located 8×8 block in the reference layer. When the co-located 8×8 block is not divided into smaller blocks, the enhancement layer macroblock is also not partitioned. Otherwise, each $M \times N$ submacroblock partition in the 8×8 reference layer block corresponds to a $(2M) \times (2N)$ macroblock partition in the enhancement layer macroblock. For the upsampled macroblock partitions, the same reference indexes as for the co-located reference layer blocks are used; and both components of the associated motion vectors are derived by scaling the corresponding reference layer motion vector components by a factor of 2.

[3]Note that for conventional dyadic spatial scalability, a macroblock in a spatial enhancement layer corresponds to an 8×8 submacroblock in its reference layer.

In addition to this new macroblock type, the SVC concept includes the possibility to use scaled motion vectors of the co-located 8×8 block in the reference layer as motion vector predictors for conventional inter-coded macroblock types. A flag for each used reference picture list that is transmitted on a macroblock partition level, i.e., for each 16×16, 16×8, 8×16, or 8×8 block, indicates whether inter-layer motion vector predictor is used. If this so-called *motion prediction flag* for a reference picture list is equal to 1, the corresponding reference indexes for the macroblock partition are not coded in the enhancement layer, but the reference indexes of the co-located reference layer macroblock partition are used, and the corresponding motion vector predictors for all blocks of the enhancement layer macroblock partition are formed by the scaled motion vectors of the co-located blocks in the reference layer. A *motion prediction flag* equal to 0 specifies that the reference indexes for the corresponding reference picture list are coded in the enhancement layer (when the number of active entries in the reference picture list is greater than 1 as specified by the slice header syntax) and that conventional spatial motion vector prediction as specified in H.264/AVC is employed for the motion vectors of the corresponding reference picture list.

b) Inter-Layer Residual Prediction: *Inter-layer residual prediction* can be employed for all inter-coded macroblocks regardless whether they are coded using the newly introduced SVC macroblock type signaled by the *base mode flag* or by using any of the conventional macroblock types. A flag is added to the macroblock syntax for spatial enhancement layers, which signals the usage of inter-layer residual prediction. When this *residual prediction flag* is equal to 1, the residual signal of the corresponding 8×8 submacroblock in the reference layer is block-wise upsampled using a bilinear filter and used as prediction for the residual signal of the enhancement layer macroblock, so that only the corresponding difference signal needs to be coded in the enhancement layer. The upsampling of the reference layer residual is done on a transform block basis in order to ensure that no filtering is applied across transform block boundaries, by which disturbing signal components could be generated [36]. Fig. 5 illustrates the visual impact of upsampling the residual by filtering across block boundary and the block-based filtering in SVC.

c) Inter-Layer Intra-Prediction: When an enhancement layer macroblock is coded with *base mode flag* equal to 1 and the co-located 8×8 submacroblock in its reference layer is intra-coded, the prediction signal of the enhancement layer macroblock is obtained by *inter-layer intra-prediction*, for which the corresponding reconstructed intra-signal of the reference layer is upsampled. For upsampling the luma component, one-dimensional 4-tap FIR filters are applied horizontally and vertically. The chroma components are upsampled by using a simple bilinear filter. Filtering is always performed across submacroblock boundaries using samples of neighboring intra-blocks. When the neighboring blocks are not intra-coded, the required samples are generated by specific border extension algorithms. In this way, it is avoided to reconstruct inter-coded macroblocks in the reference layer and thus, so-called *single-loop decoding* is provided [37], [38], which will be further explained in Section V-B.3. To prevent disturbing signal components in the prediction signal, the H.264/AVC deblocking filter is applied to the reconstructed intra-signal of the reference layer before upsampling.

2) Generalized Spatial Scalability: Similar to H.262|MPEG-2 Video and MPEG-4 Visual, SVC supports spatial scalable coding with arbitrary resolution ratios. The only restriction is that neither the horizontal nor the vertical resolution can decrease from one layer to the next. The SVC design further includes the possibility that an enhancement layer picture represents only a selected rectangular area of its corresponding reference layer picture, which is coded with a higher or identical spatial resolution. Alternatively, the enhancement layer picture may contain additional parts beyond the borders of the reference layer picture. This reference and enhancement layer *cropping*, which may also be combined, can even be modified on a picture-by-picture basis.

Furthermore, the SVC design also includes tools for spatial scalable coding of interlaced sources. For both extensions, the generalized spatial scalable coding with arbitrary resolution ratios and cropping as well as for the spatial scalable coding of interlaced sources, the three basic inter-layer prediction concepts are maintained. But especially the derivation process for motion parameters as well as the design of appropriate upsampling filters for residual and intra-blocks needed to be generalized. For a detailed description of these extensions, the reader is referred to [34] and [35].

It should be noted that in an extreme case of spatial scalable coding, both the reference and the enhancement layer may have the same spatial resolution and the cropping may be aligned with macroblock boundaries. As a specific feature of this configuration, the deblocking of the reference layer intra-signal for inter-layer intra-prediction is omitted, since the transform block boundaries in the reference layer and the enhancement layer are aligned. Furthermore, inter-layer intra- and residual-prediction are directly performed in the transform coefficient domain in order to reduce the decoding complexity. When a reference layer macroblock contains at least one nonzero transform coefficient, the co-located enhancement layer macroblock has to use the same luma transform size (4×4 or 8×8) as the reference layer macroblock.

3) Complexity Considerations: As already pointed out, the possibility of employing inter-layer intra-prediction is restricted to selected enhancement layer macroblocks, although coding efficiency can typically be improved (see Section V-B.4) by generally allowing this prediction mode in an enhancement layer, as it was done in the initial design [33]. In [21] and [37], however, it was shown that decoder complexity can be significantly reduced by constraining the usage of inter-layer intra-prediction. The idea behind this so-called *constrained inter-layer prediction* is to avoid the computationally complex and memory access intensive operations of motion compensation and deblocking for inter-coded macroblocks in the reference layer. Consequently, the usage of inter-layer intra-prediction is only allowed for enhancement layer macroblocks, for which the co-located reference layer signal is intra-coded. It is further required that all layers that are used for inter-layer prediction of higher layers are coded using constrained intra-prediction, so that the intra-coded macroblocks of the reference layers can be constructed without reconstructing any inter-coded macroblock.

Under these restrictions, which are mandatory in SVC, each supported layer can be decoded with a *single motion compensation loop*. Thus, the overhead in decoder complexity for SVC compared to single-layer coding is smaller than that for prior video coding standards, which all require multiple motion compensation loops at the decoder side. Additionally, it should be mentioned that each quality or spatial enhancement layer NAL unit can be parsed independently of the lower layer NAL units, which provides further opportunities for reducing the complexity of decoder implementations [39].

4) Coding Efficiency: The effectiveness of the SVC inter-layer prediction techniques for spatial scalable coding has been evaluated in comparison to single-layer coding and simulcast. For this purpose, the base layer was coded at a fixed bit rate, whereas for encoding the spatial enhancement layer, the bit rate as well as the amount of enabled inter-layer prediction mechanisms was varied. Additional simulations have been performed by allowing an unconstrained inter-layer intra-prediction and hence decoding with multiple motion compensation loops. Only the first access unit was intra-coded and CABAC was used as entropy coding method. Simulations have been carried out for a GOP size of 16 pictures as well as for IPPPP coding. All encoders have been rate-distortion optimized according to [14]. For each access unit, first the base layer is encoded, and given the corresponding coding parameters, the enhancement layer is coded [31]. The inter-layer prediction tools are considered as additional coding options for the enhancement layer in the operational encoder control. The lower resolution sequences have been generated following the method in [31]. The simulation results for the sequences "City" and "Crew" with spatial scalability from CIF (352×288) to 4CIF (704×576) and a frame rate of 30 Hz are depicted in Fig. 6. For both sequences, results for a GOP size of 16 pictures (providing 5 temporal layers) are presented while for "Crew," also a result for IPPP coding (GOP size of 1 picture) is depicted. For all cases, all inter-layer prediction (ILP) tools, given as intra (I), motion (M), and residual (R) prediction, improve the coding efficiency in comparison to simulcast. However, the effectiveness of a tool or a combination of tools strongly depends on the sequence characteristics

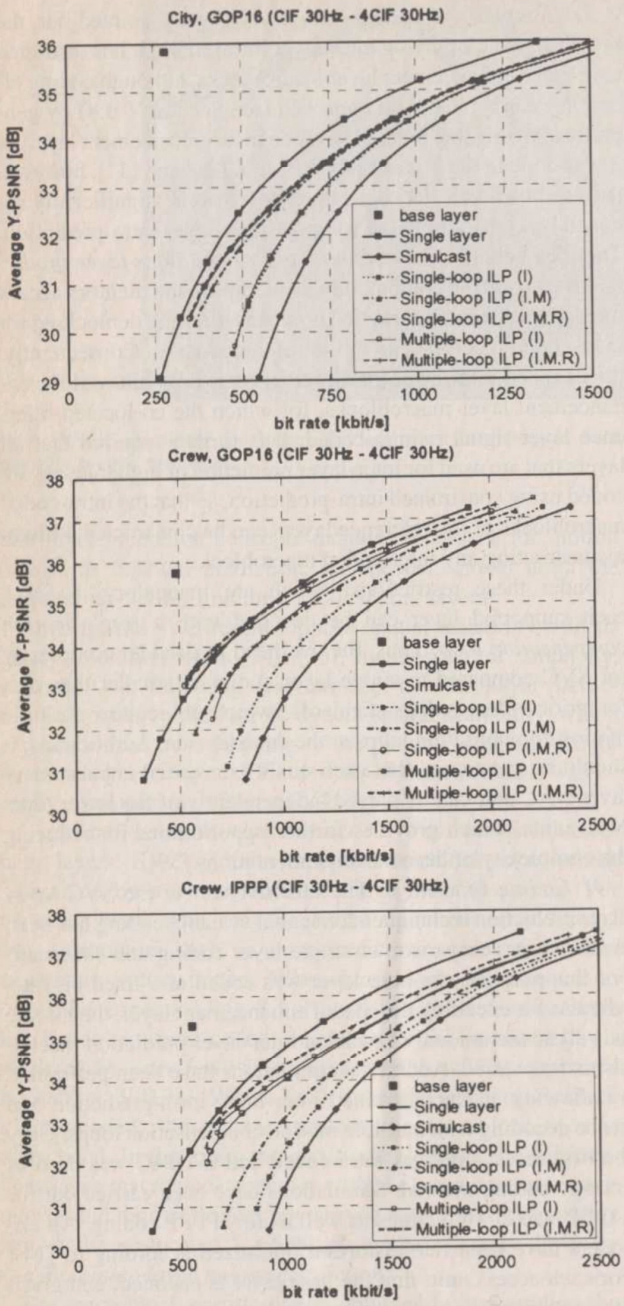


Fig. 6. Efficiency analysis of the inter-layer prediction concepts in SVC for different sequences and prediction structures. The rate-distortion point for the base layer is plotted as a solid rectangle inside the diagrams, but it should be noted that it corresponds to a different spatial resolution.

and the prediction structure. While the result for the sequence "Crew" and a GOP size of 16 pictures is very close to that for single-layer coding, some losses are visible for "City," which is the worst performing sequence in our test set. Moreover, as illustrated for "Crew," the overall performance of SVC compared to single-layer coding reduces when moving from a GOP size of 16 pictures to IPPP coding.

Multiple-loop decoding can further improve the coding efficiency as illustrated in Fig. 6. But the gain is often minor and comes at the price of a significant increase in decoder complexity. It is worth noting that the rate-distortion performance for multiloop decoding using only inter-layer intra-prediction ("multiple-loop ILP (I)") is usually worse than that of the "single-loop ILP (I,M,R)" case, where the latter corresponds to the fully featured SVC design while the former is conceptually comparable to the scalable profiles of H.262 | MPEG-2 Video, H.263, or MPEG-4 Visual. However, it should be noted that the hierarchical prediction structures which not only improve the overall coding efficiency but also the effectiveness of the inter-layer prediction mechanisms, are not supported in these prior video coding standards.

5) Encoder Control: The encoder control as used in the JSVM [31] for multilayer coding represents a bottom-up process. For each access unit, first the coding parameters of the base layer are determined, and given these data, the enhancement layers are coded in increasing order of their layer identifier D. Hence, the results in Fig. 6 show only losses for the enhancement layer while the base layer performance is identical to that for single-layer H.264/AVC coding. However, this encoder control concept might limit the achievable enhancement layer coding efficiency, since the chosen base layer coding parameters are only optimized for the base layer, but they are not necessarily suitable for an efficient enhancement layer coding. A similar effect might be observed when using different downsampled sequences as input for the base layer coding. While the encoder control for the base layer minimizes the reconstruction error relative to each individual downsampled "original," the different obtained base layer coding parameters may result in more or less reusable data for the enhancement layer coding, although the reconstructed base layer sequences may have a subjectively comparable reconstruction quality.

First experimental results for an improved multilayer encoder control which takes into account the impact of the base layer coding decisions on the rate-distortion efficiency of the enhancement layers are presented in [40]. The algorithm determines the base layer coding parameters using a weighted sum of the Lagrangian costs for base and enhancement layer. Via the corresponding weighting factor it is possible to tradeoff base and enhancement layer coding efficiency. In Fig. 7, an example result for spatial scalable coding with hierarchical B-pictures and a GOP size of 16 pictures is shown. Four scalable bit streams have been coded with both the JSVM and the optimized encoder control. The quantization parameter QP_E for the enhancement layer was set to $\mathrm{QP}_B + 4$, with QP_B being the quantization parameter for the base layer. With the optimized encoder control the SVC coding efficiency can be controlled in a way that the bit rate increase relative to single layer coding for the same fidelity is always less than or equal to 10% for both the base and the enhancement layer.

C. Quality Scalability

Quality scalability can be considered as a special case of spatial scalability with identical picture sizes for base and enhancement layer. As already mentioned in Section V-B, this case is supported by the general concept for spatial scalable coding and it is also referred to as *coarse-grain quality scalable coding* (CGS). The same inter-layer prediction mechanisms as

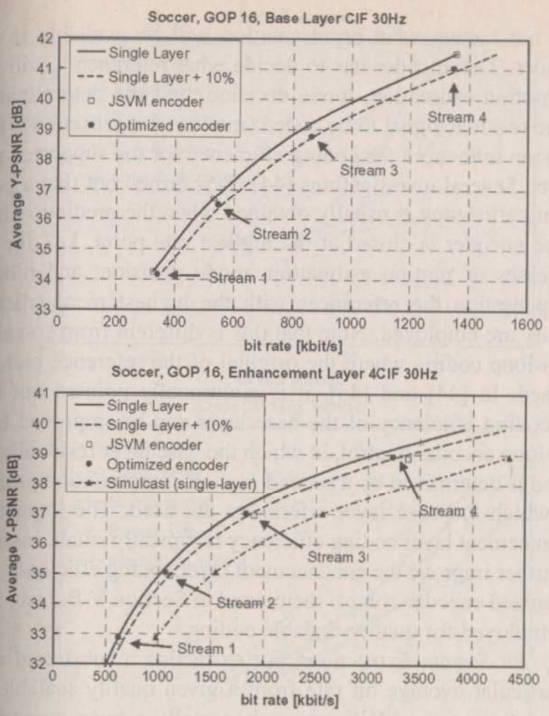


Fig. 7. Experimental results for spatial scalable coding (from CIF to 4CIF, 30 Hz) of the sequence "Soccer" using an optimized encoder control.

for spatial scalable coding are employed, but without using the corresponding upsampling operations and the inter-layer deblocking for intra-coded reference layer macroblocks. Furthermore, the inter-layer intra- and residual-prediction are directly performed in the transform domain. When utilizing inter-layer prediction for coarse-grain quality scalability in SVC, a refinement of texture information is typically achieved by requantizing the residual texture signal in the enhancement layer with a smaller quantization step size relative to that used for the preceding CGS layer.

However, this multilayer concept for quality scalable coding only allows a few selected bit rates to be supported in a scalable bit stream. In general, the number of supported rate points is identical to the number of layers. Switching between different CGS layers can only be done at defined points in the bit stream (cp. Section VI). Furthermore, as will be demonstrated in Section V-C.4, the multilayer concept for quality scalable coding becomes less efficient, when the relative rate difference between successive CGS layers gets smaller.

Especially for increasing the flexibility of bit stream adaptation and error robustness, but also for improving the coding efficiency for bit streams that have to provide a variety of bit rates, a variation of the CGS approach, which is also referred to as *medium-grain quality scalability* (MGS), is included in the SVC design. The differences to the CGS concept are a modified high-level signaling (cp. Section VI), which allows a switching between different MGS layers in any access unit, and the so-called *key picture concept* (cp. Section V-C.1), which allows the adjustment of a suitable tradeoff between drift and enhancement layer coding efficiency for hierarchical prediction structures. With the MGS concept, any enhancement layer NAL unit can be discarded from a quality scalable bit stream, and thus packet-based quality scalable coding is provided. SVC additionally provides the possibility to distribute the enhancement layer transform coefficients among several slices. To this end, the first and the last scan index for transform coefficients are signaled in the slice headers, and the slice data only include transform coefficient levels for scan indexes inside the signaled range. Thus, the information for a quality refinement picture that corresponds to a certain quantization steps size can be distributed over several NAL units corresponding to different quality refinement layers with each of them containing refinement coefficients for particular transform basis functions only (cp. [41]). In addition, the macroblocks of a picture (and a quality refinement layer) can be partitioned into several slices as in standard H.264/AVC.

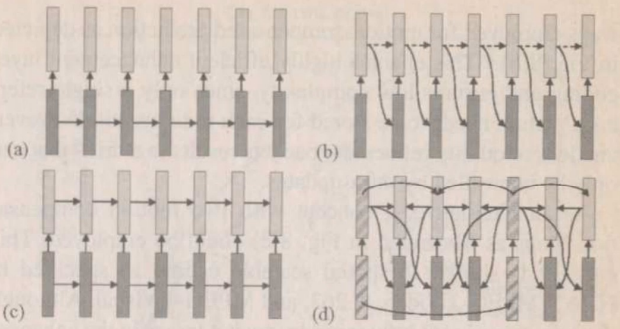


Fig. 8. Various concepts for trading off enhancement layer coding efficiency and drift for packet-based quality scalable coding. (a) Base layer only control. (b) Enhancement layer only control. (c) Two-loop control. (d) Key picture concept of SVC for hierarchical prediction structures, where key pictures are marked by the hatched boxes.

1) Controlling Drift in Quality Scalable Coding: The process of motion-compensated prediction for packet-based quality scalable coding has to be carefully designed, since it determines the tradeoff between enhancement layer coding efficiency and *drift* (cp. [42]). Drift describes the effect that the motion-compensated prediction loops at encoder and decoder are not synchronized, e.g., because quality refinement packets are discarded from a bit stream. Fig. 8 illustrates different concepts for trading off enhancement layer coding efficiency and drift for packet-based quality scalable coding.

For *fine-grain quality scalable* (FGS) coding in MPEG-4 Visual, the prediction structure was chosen in a way that drift is completely omitted. As illustrated in Fig. 8(a), motion compensation in MPEG-4 FGS is only performed using the base layer reconstruction as reference, and thus any loss or modification of a quality refinement packet does not have any impact on the motion compensation loop. The drawback of this approach, however, is that it significantly decreases enhancement layer coding efficiency in comparison to single-layer coding. Since only base layer reconstruction signals are used for motion-compensated prediction, the portion of bit rate that is spent for encoding MPEG-4 FGS enhancement layers of a picture cannot be exploited for the coding of following pictures that use this picture as reference.

For quality scalable coding in H.262 | MPEG-2 Video, the other extreme case of possible prediction structures was specified. Here, the reference with the highest available quality is al-

ways employed for motion-compensated prediction as depicted in Fig. 8(b).[4] This enables highly efficient enhancement layer coding and ensures low complexity, since only a single reference picture needs to be stored for each time instant. However, any loss of quality refinement packets results in a drift[5] that can only be controlled by intra-updates.

As an alternative, a concept with two motion compensation loops as illustrated in Fig. 8(c) could be employed. This concept is similar to spatial scalable coding as specified in H.262 | MPEG-2 Video, H.263, and MPEG-4 Visual. Although the base layer is not influenced by packet losses in the enhancement layer, any loss of a quality refinement packet results in a drift for the enhancement layer reconstruction.

For MGS coding in SVC an alternative approach using so-called *key pictures* [21] has been introduced. For each picture a flag is transmitted, which signals whether the base quality reconstruction or the enhancement layer reconstruction of the reference pictures is employed for motion-compensated prediction. In order to limit the memory requirements, a second syntax element signals whether the base quality representation of a picture is additionally reconstructed and stored in the DPB. In order to limit the decoding overhead for such key pictures, SVC specifies that motion parameters must not change between the base and enhancement layer representations of key pictures, and thus also for key pictures, the decoding can be done with a single motion-compensation loop. Fig. 8(d) illustrates how the key picture concept can be efficiently combined with hierarchical prediction structures.

All pictures of the coarsest temporal layer are transmitted as key pictures, and only for these pictures the base quality reconstruction is inserted in the DPB. Thus, no drift is introduced in the motion compensation loop of the coarsest temporal layer. In contrast to that, all temporal refinement pictures typically use the reference with the highest available quality for motion-compensated prediction, which enables a high coding efficiency for these pictures. Since the key pictures serve as resynchronization points between encoder and decoder reconstruction, drift propagation is efficiently limited to neighboring pictures of higher temporal layers. The tradeoff between enhancement layer coding efficiency and drift can be adjusted by the choice of the GOP size or the number of hierarchy stages. It should be noted that both the quality scalability structure in H.262 | MPEG-2 Video (no picture is coded as key picture) and the FGS coding approach in MPEG-4 Visual (all pictures are coded as key pictures) basically represent special cases of the SVC key picture concept.

2) Encoder Control: As described in the previous section, except for key pictures, motion-compensated prediction for quality scalable coding is always performed by employing the highest available quality of the corresponding reference pictures. However, during the encoding process for MGS layers it is not known what representation will be available in the decoder. The encoder has to decide what reference it will use for motion estimation, mode decision, and the determination of the residual signal to be coded (motion compensation). This decision influences the coding efficiency for the supported rate points. Several investigations [44], [45] turned out that a good coding efficiency is usually obtained when the prediction loop in the encoder is closed at the highest rate point, i.e., for the processes of motion estimation, mode decision, and motion compensation the references with the highest reconstruction quality are employed. Note that this is different from so-called open-loop coding where the original of the reference pictures is used. In [44] and [45], it is additionally pointed out that the coding efficiency of the base layer can be improved by a two-loop encoder control, in which the base layer residual to be coded is determined by a second motion compensation process for which the base layer references are used. The impact on enhancement layer coding efficiency is typically small. In order to further improve the enhancement layer coding efficiency, the optimized encoder control mentioned in Section V-B.5 can also be employed for quality scalable coding.

3) Bit Stream Extraction: For extracting a substream with a particular average bit rate from a given quality scalable bit stream (using the MGS approach) usually a huge number of possibilities exist. The same average bit rate can be adjusted by discarding different quality refinement NAL units. Thus, the obtained average reconstruction error that corresponds to the given target bit rate may depend on the used extraction method. A very simple method may consist of randomly discarding MGS refinement packets until the requested bit rate is reached. Alternatively, in a more sophisticated method, a priority identifier is assigned to each coded slice NAL unit by an encoder. During the bit stream extraction process, at first, coded slice NAL units with the lowest priority are discarded, and when the target bit rate is not already reached coded slice NAL units of the next priority class are discarded, etc. The priority identifiers can either be fixed by the encoder based on the employed coder structure or determined by a rate-distortion analysis. The SVC syntax (cp. Section VI) provides different means for including such priority information in a bit stream. For more detailed information about the concept of optimized bit stream extraction, which is also referred to as *priority layers*, the reader is referred to [46].

4) Coding Efficiency: In a first experiment the different concepts for controlling drift, as discussed in Section V-C.1, are evaluated for hierarchical B-pictures with a GOP size of 16 pictures. With exception of the 2-loop control, all configurations could be realized with an SVC compliant encoder. Results for the sequences "City" and "Crew" are summarized in Fig. 9. For these simulations, the intermediate rate points for all drift control concepts were obtained by randomly discarding quality refinement NAL units.

When the motion compensation loop is closed at the base layer (BL-only control) as in MPEG-4 FGS [corresponding to Fig. 8(a)], no drift occurs, but the enhancement layer coding efficiency is very low, especially for sequences like "City" for which motion-compensated prediction works very well.

By closing the loop only at the enhancement layer (EL-only control), as it is done in the quality scalable mode of H.262 | MPEG-2 Video [corresponding to Fig. 8(b)], a high

[4]For a generalization of the basic concept, Fig. 8(b) indicates (by dashed arrows) that motion parameters may be changed between base and enhancement layer, although this is not supported in H.262 | MPEG-2 Video.

[5]Since H.262 | MPEG-2 Video does not allow partial discarding of quality refinement packets inside a video sequence, the drift issue can be completely avoided in conforming H.262 | MPEG-2 Video bit streams by controlling the reconstruction quality of both the base and the enhancement layer during encoding (cp. Section V-C.4).

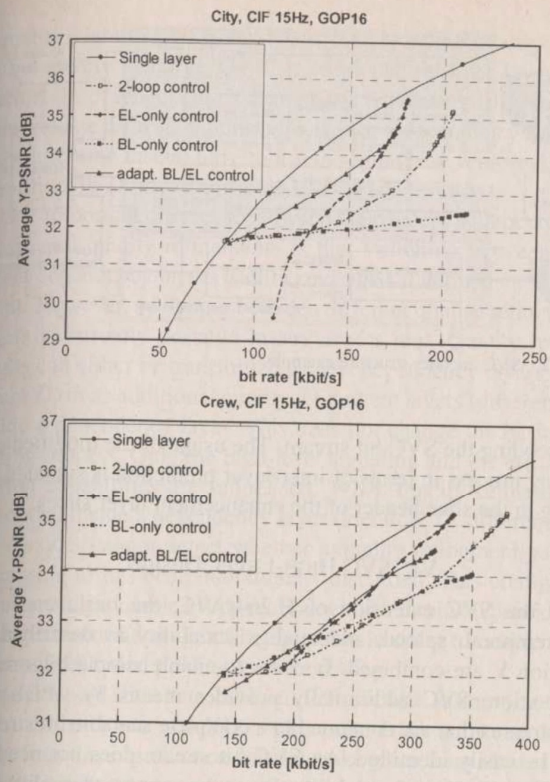


Fig. 9. Comparison of drift control concepts with different tradeoffs between enhancement layer coding efficiency and drift for the sequences "City" and "Crew" in CIF resolution and a frame rate of 15 Hz.

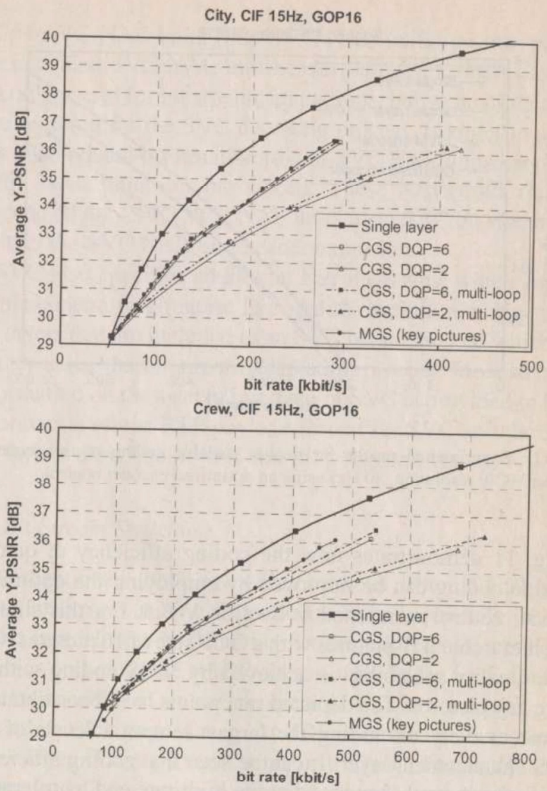


Fig. 10. Comparison of CGS and MGS scalable coding with different configurations for the sequences "City" and "Crew" in CIF resolution and a frame rate of 15 Hz.

enhancement layer coding efficiency can be achieved. But the discarding of enhancement layer packets typically results in a serious drift, and the reconstructed video quickly becomes unusable. It should be noted that the behavior of the enhancement layer only control highly depends on the employed encoder control concept. For the simulations in Fig. 9, the encoder control was operated with the goal to optimize the enhancement layer coding efficiency. With a different encoder control, it is possible to obtain a base layer that has the same coding efficiency as a single-layer bit stream. However, such an encoder control significantly reduces the enhancement layer coding efficiency. And regardless of the used encoder control, a partial loss of the enhancement layer NAL units always results in a significant drift.

A similar behavior can also be observed for the 2-loop control [corresponding to Fig. 8(c)], but here the reconstruction quality stabilizes for low rates at the base layer level. For the sequence "Crew" the corresponding impact is less obvious, since a substantial portion of macroblocks is intra-coded and the differences only apply for inter-coding.

With the SVC key picture concept [adapt. BL/EL control—corresponding to Fig. 8(d)], in which the pictures of the coarsest temporal level are coded as key pictures, a reasonable coding efficiency for the entire supported rate interval can be achieved in connection with hierarchical prediction structures. The results in Fig. 9 also show that the SVC design can only provide a suitable coding efficiency for quality scalable coding with a wide range of supported bit rates when hierarchical prediction structures are employed.

In a second experiment different configurations for providing quality scalability are evaluated. In Fig. 10, the coding efficiency of CGS coding and MGS coding with key pictures is compared to that of single-layer coding for hierarchical B-pictures with a GOP size of 16 pictures. For the quality scalable bit streams, the bit rate interval between the lowest and highest supported rate point corresponds to a QP difference of 12, i.e., the enhancement layer quantization step is equal to 1/4th of the base layer quantization step size. By comparing different CGS configurations with different choices of *delta QP* (DQP), which is the numerical difference between the QP values of two successive layers, it can be seen that coding efficiency generally decreases with an increasing number of supported rate points, i.e., with decreasing DQP. The diagrams also contain rate-distortion curves for CGS with multiple-loop decoding, which is not supported by the SVC design. As already observed for spatial scalable coding, multiple-loop decoding for CGS increases coding efficiency only slightly and therefore, it does not justify the corresponding increase in decoder complexity relative to single-loop decoding. Additionally, Fig. 10 also shows the coding efficiency of the more flexible MGS coding with the usage of the key picture concept and a DQP of 6. The improved coding efficiency at the highest rate point and the reduced coding efficiency at the lowest rate point for the MGS runs in comparison to the CGS runs with DQP equal to 6 are a result of the improved encoder control for MGS, which is described in Section V-C.2. It should be noted that with MGS coding, the number of supported rate points is significantly increased in comparison to CGS coding.

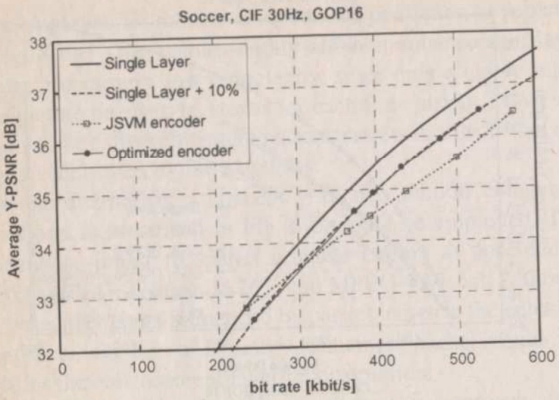


Fig. 11. Experimental results for quality scalable coding of the sequence "Soccer" (CIF resolution, 30 Hz) using an optimized encoder control.

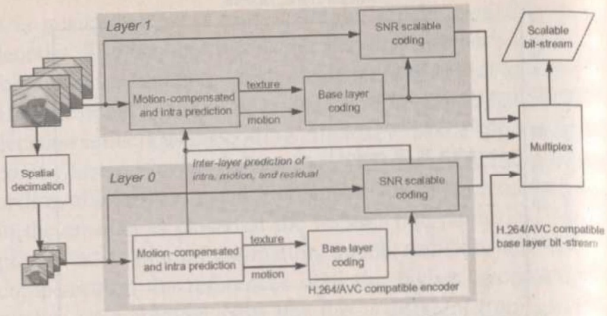


Fig. 12. SVC encoder structure example.

Fig. 11 demonstrates how the coding efficiency of quality scalable coding can be improved by employing the optimized encoder control mentioned in Section V-B.5. For this simulation, hierarchical B-pictures with a GOP size of 16 pictures were used. Quality scalability is achieved by MGS coding without using key pictures. The depicted rate points have been obtained by successively discarding the largest temporal levels of the MGS enhancement layer. It can be seen that coding efficiency can be significantly improved at the high-rate end by tolerating a coding efficiency loss for the lowest rate point. With the optimized encoder control it was possible to limit the bit rate increase compared to single-layer coding at the same fidelity to about 10% over the entire supported bit rate range.

5) SVC-to-H.264/AVC Rewriting: The SVC design also supports the creation of quality scalable bit streams that can be converted into bit streams that conform to one of the nonscalable H.264/AVC profiles by using a low-complexity rewriting process [47]. For this mode of quality scalability, the same syntax as for CGS or MGS is used, but two aspects of the decoding process are modified.

1) For the inter-layer intra-prediction, the prediction signal is not formed by the reconstructed intra-signal of the reference layer, but instead the spatial intra-prediction modes are inferred from the co-located reference layer blocks, and a spatial intra-prediction as in single-layer H.264/AVC coding is performed in the target layer, i.e., the highest quality refinement layer that is decoded for a picture. Additionally, the residual signal is predicted as for motion-compensated macroblock types.
2) The residual prediction for inter-coded macroblocks and for inter-layer intra-coded macroblocks (*base mode flag* is equal to 1 and the co-located reference layer blocks are intra-coded) is performed in the transform coefficient level domain, i.e., not the scaled transform coefficients, but the quantization levels for transform coefficients are scaled and accumulated.

These two modifications ensure that such a quality scalable bit stream can be converted into a nonscalable H.264/AVC bit stream that yields exactly the same decoding result as the quality scalable SVC bit stream. The conversion can be achieved by a rewriting process which is significantly less complex than transcoding the SVC bit stream. The usage of the modified decoding process in terms of inter-layer prediction is signaled by a flag in the slice header of the enhancement layer slices.

VI. SVC High-Level Design

In the SVC extension of H.264/AVC, the basic concepts for temporal, spatial, and quality scalability as described in Section V are combined. In order to enable simple bit stream adaptation, SVC additionally provides means by which the substreams that are contained in a complete scalable bit stream can be easily identified. An SVC bit stream does not need to provide all types of scalability. Since the support of quality and spatial scalability usually comes along with a loss in coding efficiency relative to single-layer coding, the tradeoff between coding efficiency and the provided degree of scalability can be adjusted according to the needs of an application. For a further comparison of spatial and quality scalability with single-layer coding, the reader is referred to [48].

A. Combined Scalability

The general concept for combining spatial, quality, and temporal scalability is illustrated in Fig. 12, which shows an example encoder structure with two spatial layers. The SVC coding structure is organized in dependency layers. A dependency layer usually represents a specific spatial resolution. In an extreme case it is also possible that the spatial resolution for two dependency layers is identical, in which case the different layers provide coarse-grain scalability (CGS) in terms of quality. Dependency layers are identified by a dependency identifier D. The spatial resolution must not decrease from one layer to the next. For each dependency layer, the basic concepts of motion-compensated prediction and intra-prediction are employed as in single-layer coding; the redundancy between dependency layers is exploited by additional inter-layer prediction concepts as explained in Section V-B.1.

Quality refinement layers inside each dependency layer are identified by a quality identifier Q. However, when a reference layer for a spatial enhancement layer (dependency layer) contains different quality representations, it needs to be signaled which of these is employed for inter-layer prediction. Therefore, SVC slices include a syntax element, which not only signals whether inter-layer prediction is employed, but also the dependency identifier D and the quality identifier Q of the corresponding reference layer. For quality refinement layers with

a quality identifier $Q > 0$, always the preceding quality layer with a quality identifier $Q - 1$ is employed for inter-layer prediction. In order to limit the memory requirement for storing intermediate representations, all slices of a dependency layer at a specific time instant have to use the same base representation identified by D and Q for inter-layer prediction.

One important difference between the concept of dependency layers and quality refinements is that switching between different dependency layers is only envisaged at defined switching point. However, switching between different quality refinement layers is virtually possible in any access unit. Quality refinements can either be transmitted as new dependency layers (different D) or as additional quality refinement layers (different Q) inside a dependency layer. This does not change the basic decoding process. Only the high-level signaling and the error-detection capabilities are influenced. When quality refinements are coded inside a dependency layer (identical D, different Q), the decoder cannot detect whether a quality refinement packet is missing or has been intentionally discarded. This configuration is mainly suitable in connection with hierarchical prediction structures and the usage of key pictures in order to enable efficient packet-based quality scalable coding.

In SVC, all slice data NAL units for a time instant together with zero or more non-VLC NAL units form an access unit. Since inter-layer prediction can only take place from a lower to a higher layer inside an access unit, spatial and quality scalability can be easily combined with temporal scalability. To all slices of an access unit the same temporal level T is assigned.

In addition to the main scalability types, temporal, spatial, and quality scalability, SVC additionally supports ROI scalability. ROI scalability can be realized via the concepts of slice groups (cp. Section IV-B), but the shape of the ROI is restricted to patterns that can be represented as a collection of macroblocks.

B. System Interface

An important goal for SVC standard is to support easy bit stream manipulation. In order to extract a substream with a reduced spatio–temporal resolution and/or bit rate, all NAL units that are not required for decoding the target resolution and/or bit rate should be removed from a bit stream. For this purpose, parameters like the dependency identifier D, the quality identifier Q, and the temporal identifier T need to be known for each coded slice NAL unit. Furthermore, it needs to be known what NAL units are required for inter-layer prediction of higher layers.

In order to assist easy bit stream manipulations, the 1-byte header of H.264/AVC is extended by additional 3 bytes for SVC NAL unit types. This extended header includes the identifiers D, Q, and T as well as additional information assisting bit stream adaptations. One of the additional syntax elements is a priority identifier P, which signals the importance of a NAL unit. It can be used either for simple bit stream adaptations with a single comparison per NAL unit or for rate-distortion optimized bit stream extraction using priority layer information (cp. Section V-C.3).

Each SVC bit stream includes a substream, which is compliant to a nonscalable profile of H.264/AVC. Standard H.264/AVC NAL units (non-SVC NAL units) do not include the extended SVC NAL unit header. However, these data are not only useful for bit stream adaptations, but some of them are also required for the SVC decoding process. In order to attach this SVC related information to non-SVC NAL units, so-called prefix NAL units are introduced. These NAL units directly precede all non-SVC VCL NAL units in an SVC bit stream and contain the SVC NAL unit header extension.

SVC also specifies additional SEI messages, which for example contain information like spatial resolution or bit rate of the layers that are included in an SVC bit stream and which can further assist the bit stream adaptation process. More detailed information on the system interface of SVC is provided in [49]. Information on the RTP payload format for SVC and the SVC file format are given in [50] and [51], respectively.

C. Bit Stream Switching

As mentioned above, switching between different quality refinement layers inside a dependency layer is possible in each access unit. However, switching between different dependency layers is only possible at IDR access units. In the SVC context, the classification of an access unit as IDR access unit generally depends on the target layer. An IDR access unit for a dependency layer D signals that the reconstruction of layer D for the current and all following access units is independent of all previously transmitted access units. Thus, it is always possible to switch to the dependency layer (or to start the decoding of the dependency layer) for which the current access unit represents an IDR access unit. But it is not required that the decoding of any other dependency layer can be started at that point. IDR access units only provide random access points for a specific dependency layer. For instance, when an access unit represents an IDR access unit for an enhancement layer and thus no motion-compensated prediction can be used, it is still possible to employ motion-compensated prediction in the lower layers in order to improve their coding efficiency.

Although SVC specifies switching between different dependency layers only for well-defined points, a decoder can be implemented in a way that at least down-switching is possible in virtually any access unit. One way is to do multiple-loop decoding. That means, when decoding an enhancement layer, the pictures of the reference layers are reconstructed and stored in additional DPBs although they are not required for decoding the enhancement layer picture. But, when the transmission switches to any of the subordinate layers in an arbitrary access unit, the decoding of this layer can be continued since an additional DPB has been operated as if the corresponding layer would have been decoded for all previous access units. Such a decoder implementation requires additional processing power. For up-switching, the decoder usually has to wait for the next IDR access unit. However, similar to random access in single-layer coding, a decoder can also immediately start the decoding of all arriving NAL units by employing suitable error concealment techniques and deferring the output of enhancement layer pictures (i.e., continuing the output of lower layer reconstructions) until the reconstruction quality for the enhancement layer has stabilized (gradual decoder refresh).

D. Profiles

Profiles and levels specify conformance points to facilitate interoperability between applications that have similar functional requirements. A profile defines a set of coding tools that can be used in generating a bit stream, whereas a level specifies constraints on certain key parameters of the bit stream. All decoders conforming to a specific profile must support all included coding tools.

The SVC Amendment of H.264/AVC specifies three profiles for SVC [10]: Scalable Baseline, Scalable High, and Scalable High Intra. The Scalable Baseline profile is mainly targeted for conversational and surveillance applications that require a low decoding complexity. In this profile, the support for spatial scalable coding is restricted to resolution ratios of 1.5 and 2 between successive spatial layers in both horizontal and vertical direction and to macroblock-aligned cropping. Furthermore, the coding tools for interlaced sources are not included in this profile. For the Scalable High profile, which was designed for broadcast, streaming, and storage applications, these restrictions are removed and spatial scalable coding with arbitrary resolution ratios and cropping parameters is supported. Quality and temporal scalable coding are supported without any restriction in both the Scalable Baseline and the Scalable High profile. Bit streams conforming to the Scalable Baseline and Scalable High profile contain a base layer bit stream that conforms to the restricted Baseline profile and the High profile of H.264/AVC [6], respectively. It should be noted that the Scalable Baseline profile supports B-slices, weighted prediction, the CABAC entropy coding, and the 8×8 luma transform in enhancement layers (CABAC and the 8×8 transform are only supported for certain levels), although the base layer has to conform to the restricted Baseline profile, which does not support these tools.

Bit streams conforming to the Scalable High Intra-profile, which was mainly designed for professional applications, contain only IDR pictures (for all layers). Beside that, the same set of coding tools as for the Scalable High profile is supported.

VII. Conclusion

In comparison to the scalable profiles of prior video coding standards, the H.264/AVC extension for SVC provides various tools for reducing the loss in coding efficiency relative to single-layer coding. The most important differences are as follows.

- The possibility to employ hierarchical prediction structures for providing temporal scalability with several layers while improving the coding efficiency and increasing the effectiveness of quality and spatial scalable coding.
- New methods for inter-layer prediction of motion and residual improving the coding efficiency of spatial scalable and quality scalable coding.
- The concept of key pictures for efficiently controlling the drift for packet-based quality scalable coding with hierarchical prediction structures.
- Single motion compensation loop decoding for spatial and quality scalable coding providing a decoder complexity close to that of single-layer coding.
- The support of a modified decoding process that allows a lossless and low-complexity rewriting of a quality scalable bit stream into a bit stream that conforms to a nonscalable H.264/AVC profile.

These new features provide SVC with a competitive rate-distortion performance while only requiring a single motion compensation loop at the decoder side. Our experiments further illustrate the following.

- Temporal scalability: can be typically achieved without losses in rate-distortion performance.
- Spatial scalability: when applying an optimized SVC encoder control, the bit rate increase relative to nonscalable H.264/AVC coding at the same fidelity can be as low as 10% for dyadic spatial scalability. It should be noted that the results typically become worse as spatial resolution of both layers decreases and results improve as spatial resolution increases.
- SNR scalability: when applying an optimized encoder control, the bit rate increase relative to nonscalable H.264/AVC coding at the same fidelity can be as low as 10% for all supported rate points when spanning a bit rate range with a factor of 2-3 between the lowest and highest supported rate point.

Appendix
Test Sequences

The test sequences that are used for simulations in this paper are summarized in Tables I and II. All sequences are in YUV 4:2:0 color format, in which the two chroma components are downsampled by a factor of two in each spatial direction. The tables specify the maximum spatial and temporal resolution of the sequences. Sequences with a lower temporal resolution are obtained by frame skipping, and sequences with a lower spatial resolution are obtained by downsampling as specified in the JSVM [22].

The test sequences are classified into a high-delay and a low-delay test set. The high-delay test set contains sequences, which have been widely used for testing purposes during the SVC development. The sequences in this set contain different amounts of detail and motion. For low-delay configurations, we used a second, self-recorded test set that is more appropriate for testing low-delay features. Since low-delay is mainly required for interactive video telephone or videoconferencing applications, the low-delay test set consists of a variety of video conferencing sequences.

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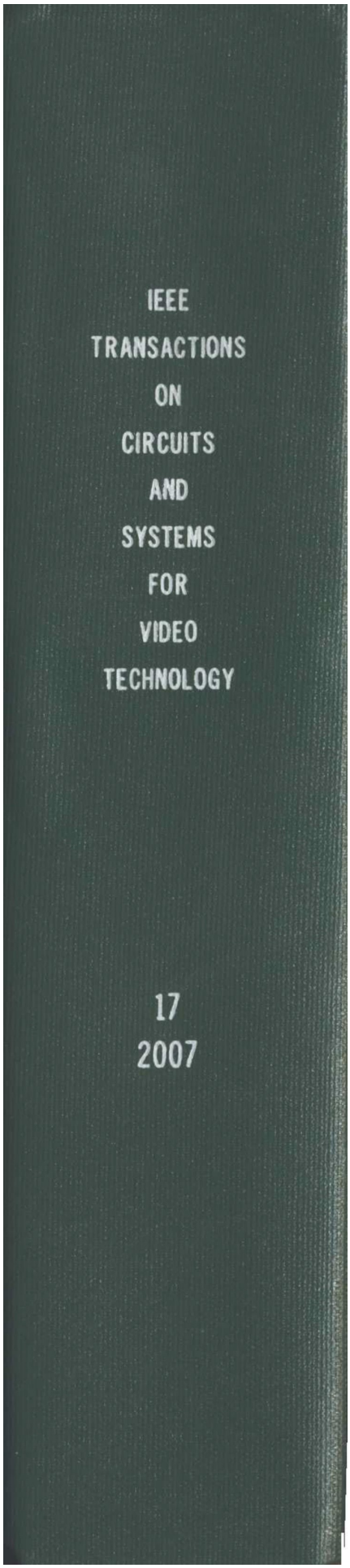
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Spatial Scalability Within the H.264/AVC Scalable Video Coding Extension

C. Andrew Segall, *Member, IEEE*, and Gary J. Sullivan, *Fellow, IEEE*

(Invited Paper)

***Abstract*—A scalable extension to the H.264/AVC video coding standard has been developed within the Joint Video Team (JVT), a joint organization of the ITU-T Video Coding Group (VCEG) and the ISO/IEC Moving Picture Experts Group (MPEG). The extension allows multiple resolutions of an image sequence to be contained in a single bit stream. In this paper, we introduce the spatially scalable extension within the resulting Scalable Video Coding standard. The high-level design is described and individual coding tools are explained. Additionally, encoder issues are identified. Finally, the performance of the design is reported.**

***Index Terms*—H.264/AVC, Scalable Video Coding (SVC), spatial scalability.**

I. Introduction

With the expectation that future applications will support a diverse range of display resolutions and transmission channel capacities, the Joint Video Team (JVT) has developed a scalable extension [1], [2] to the state-of-the-art H.264/AVC video coding standard [3]–[6]. This extension is commonly known as Scalable Video Coding (SVC) and it provides support for multiple display resolutions within a single compressed bit stream (or in hierarchically related bit streams), which is referred to here as *spatial scalability*. Additionally, the SVC extensions support combinations of *temporal scalability* (frame rate enhancement) and *quality scalability* (fidelity enhancement for pictures of the same resolution) with the spatial scalability feature [2]. This is achieved while balancing both decoder complexity and coding efficiency.

The resolution diversity of current display devices motivates the need for spatial scalability. Specifically, larger format, high definition displays are becoming common in consumer applications, with displays containing over two million pixels readily available. By contrast, lower resolution displays with between ten thousand and one hundred thousand pixels are also popular in applications constrained by size, power and weight. Unfortunately, transmitting a single representation of a video sequence to the range of display resolutions available in the market is impractical. For example, it is rarely justifiable to design a device with low display resolution with the capacity for decoding and down-sampling high-resolution video material. Such a requirement could increase the cost and power of the device to the point of exceeding the very constraints that determined its display resolution. In addition, sending the high-resolution details that are ultimately not shown on the display for such a device is a waste of its receiving channel bit rate.

Diverse, limited, and time-varying channel capacity provides a second motivation for spatial scalability. Here, the concern is that channel capacity may preclude the reliable transmission of high-resolution video to specific devices or at specific time instances. Spatial scalability allows for the rapid bit rate adaptation that can be a necessity in such scenarios. This bit rate adaptation is achieved without transcoding operations or feedback to a complex real-time encoding process, both of which can introduce unacceptable complexity and delay.

The purpose of this paper is to discuss key concepts of spatial scalability within the SVC extension. This project is the fourth in a historical series of efforts to standardize spatially SVC schemes (after prior efforts in MPEG-2 [7], [8], H.263 Annex O [9], and MPEG-4 part 2 [10]), although the prior designs were basically not successful in terms of industry adoption. This paper points out several ways in which the new design addresses the problems of those prior approaches.

The rest of this paper is organized as follows. Section II provides an overview of H.264/AVC spatially scalable coding and compares it to alternative scalable approaches. In Section III, the specific coding tools within the spatial SVC design are described. In Section IV, encoder issues related to spatial SVC are considered. In Section V, the performance of the spatial SVC extension is presented. Finally, conclusions are provided in Section VI.

II. Overview

The SVC extension of H.264/AVC provides a mechanism for reusing an encoded lower resolution version of an image sequence for the coding of a corresponding higher resolution sequence. This is shown in Fig. 1, where a diagram of a hypothetical SVC encoder is provided. Subsequent sections discuss the specific tools introduced in the SVC extension. However, to better aid in the understanding of the SVC design, this section focuses on higher level concepts. We begin by identifying basic concepts and definitions necessary for discussion of the SVC design. Then, we consider the high level spatial relationship between resolutions in a bit stream. Finally, we summarize

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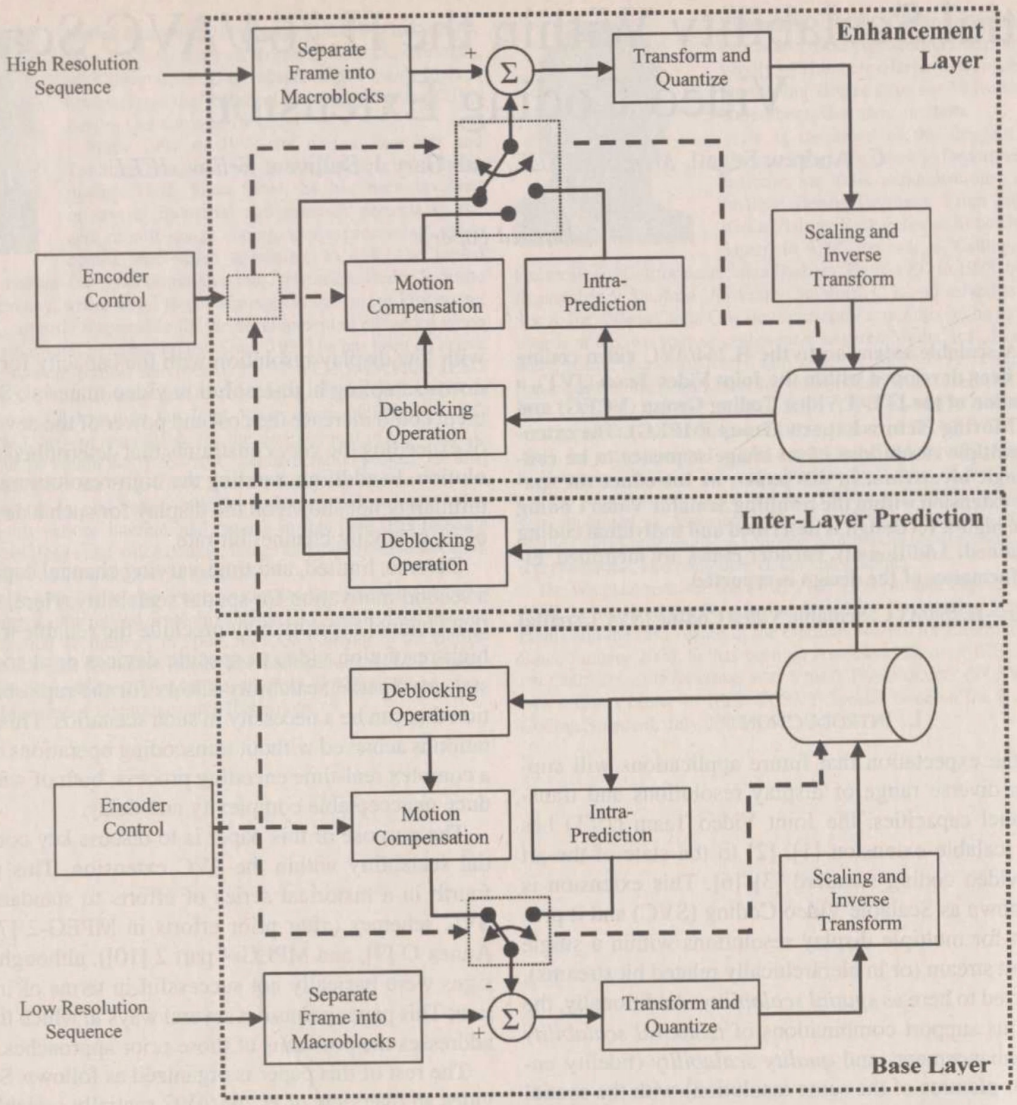


Fig. 1. High-level diagram of spatial scalability in the SVC design. The "base layer" encoder takes a lower resolution video sequence as input and encodes it with the H.264/AVC video coding standard while conforming to a legacy profile. The enhancement layer encoder takes a higher resolution sequence as input. The higher resolution sequence can be encoded with ordinary H.264/AVC technologies. Moreover, inter-layer prediction can be used to provide additional coding choices. For the case of intra-picture coded blocks in the base layer, reconstructed intensities provide a prediction for the enhancement layer. For the case of inter-picture coded blocks in the base layer, enhancement layer motion vectors and residual difference information can be predicted from the base layer. Further resolution layers can be added in an analogous fashion and can utilize either the base layer or previously transmitted enhancement layers for inter-layer prediction. Moreover, other forms of SVC (temporal or quality) enhancement may also be present.

two key design concepts in the SVC extension—image pyramids and single-loop decoding.

A. Basic Concepts

The basic mission of a scalable design is two-fold: 1) to minimize the coding efficiency loss relative to single-layer coding; and 2) to minimize the complexity increase (especially for decoders) relative to single-layer coding. By *single-layer coding*, we refer to the coding of a video sequence without providing the scalability functionality. Unless a result with coding efficiency significantly superior to a simulcast solution can be obtained, a scalable solution with any complexity penalty is useless. By *simulcast*, we refer to the coding of both source video sequences of a scalable scenario as entirely separate single-layer bit streams and transmitting them using the sum of the two bit rates. The challenge here is considerable—among the three typical basic forms of bit stream scalability, i.e., spatial, temporal, and quality, the spatial form seems to be the most difficult in which to achieve significant superiority to a simulcast solution. One dominant reason for this is the focus of the JVT on supporting lower resolution versions of image sequences with high visual quality, as opposed to lower resolution representations that provide high coding efficiency.

The lowest resolution video data in a spatially scalable system is sometimes referred to as the *base layer* (especially when it is decodable by an ordinary nonscalable single-layer decoder), and the higher resolution video data is often referred to as the *enhancement layer*. Processes that determine or predict the value

of enhancement layer data from previously reconstructed data of a lower resolution layer at the same time instance are referred to as *inter-layer* prediction processes, and the source for the prediction is referred to as the *reference layer*. Other forms of prediction include *inter-picture* prediction, involving prediction operating temporally between different pictures of the same resolution layer, and *intra-picture* prediction, involving prediction operating spatially within the same picture of one particular resolution layer.

From a video coding specification perspective, the set of data comprising a SVC representation is treated as a single bit stream. However, from a systems multiplex or file storage perspective, the data might often be handled differently—as distinct hierarchically related streams of content that are coordinated using decoding timestamps or other such mechanisms. In this fashion, a system can ease the handling of the data, such as enabling channel bit rate adaptation or ensuring that legacy decoders that do not support scalability are presented with only the base layer for decoding.

Some degree of familiarity with the concepts of the original H.264/AVC standard is assumed in the presentation provided herein, such as the concepts of macroblocks, motion partitions, biprediction, inter-picture prediction using multiple reference pictures, and reference picture lists. Readers unfamiliar with this background information may benefit from referring to [3]–[6]. Moreover, one topic that is somewhat neglected in this presentation is that of interlaced-scan video content. Herein the principles of the spatial SVC design are explained under the assumption of frame-structured progressive-scan pictures, so that the concepts can be described without the need to consider the details of the handling of interlaced fields and frames. The application of these SVC concepts to interlaced video is straightforward for those familiar with interlaced video coding using H.264/AVC. For further information about interlaced video support in the SVC context, the reader is referred to [11]. The overview of SVC in general that is found in [2] will also be of interest to many readers.

An additional simplification used in much of the discussion for this overview paper is to primarily consider a bit stream containing only two layers—a lower resolution base layer and a higher resolution spatial scalability enhancement layer. In fact, the SVC design fully supports multilayer scenarios including multiple spatial scalability layers and the mixing of spatial scalability layers with other layers that provide temporal or quality scalability. Considerable flexibility is also provided in regard to the selection of the reference layer for each enhancement layer, such that a bit stream can contain branching dependency structures.

As with prior international standards for video coding (scalable and nonscalable), the scope of the standard is limited to specifying the decoding process and the format of the syntax. Encoder designers are free to use any encoding algorithms they wish, so long as the bit stream they produce conforms to the format specification. Any kind of preprocessing is also allowed prior to encoding, and decoding devices are allowed to contain any sort of post-processing, error and loss concealment techniques, and display-related customization.

B. Inter-Layer Spatial Relationships and Profile Constraints

An important feature of the SVC design, from a high-level functionality perspective, is the ability for the lower resolution and higher resolution pictures in a spatially scalable bit stream to represent different regions of a video scene. For example, a system may transmit standard definition television content, with a picture aspect ratio of 4:3, as a base layer and high definition television content, with a picture aspect ratio of 16:9, in a higher resolution enhancement layer. Such a use case requires cropping and offsetting the origins of the picture regions in addition to scaling, as the lower resolution layer signal may not represent the entire extent of the higher resolution sequence (and vice versa). The common "pan and scan" technique used on standard-definition DVDs for converting wide screen data for display on a 4:3 display is an example of a more limited form of such display adaptation. The SVC extension supports such capability in a flexible but straightforward manner. Relative positioning and windowing parameters are provided in picture-level syntax structures, so that flexible cropping, scaling, and alignment relationships can not only be supported but may be varied on a picture-by-picture basis.

However, such flexibility can be constrained to simplify the use cases for particular applications. In particular, the SVC extension includes the definition of three *profiles* of the design. These are the "Scalable Baseline" profile, the "Scalable High" profile, and the "Scalable High Intra" profile. While the latter two profiles support full spatial SVC flexibility, the Scalable Baseline profile imposes the following constraints to enable simplified application scenarios.

- The width and height of the scaled regions of lower resolution and higher resolution pictures must have the same scaling ratio, and this ratio can only have the value 1.5 or 2.
- The spatial offsets specifying the relative location of the upper left corner of the lower and higher resolution picture regions must be multiples of 16 both horizontally and vertically (i.e., they must be in units of macroblocks).

The case using a scaling ratio of 2 with spatial offset constraints as noted above is often referred to as *dyadic* spatial scalability, whereas the more general case is known as *extended* spatial scalability [12].

C. Image Pyramids and Related Coarse-to-Fine Hierarchies

Image pyramids describe a relationship between lower resolution and higher resolution versions of an image.[1] This relationship is found in a variety of image and video processing scenarios, and image pyramids have been incorporated into a variety of applications, e.g., [13]–[19], as well as previous scalable efforts in the video coding standards [7]–[10]. In the SVC extension, a coarse-to-fine hierarchy of images is also used for spatial scalability. The original high-resolution image sequence is converted to lower resolutions by filtering and decimating. Then, the sequence of pictures at the lowest of these resolutions is coded in a manner such that it can be decoded independently. Each higher resolution video sequence is coded relative to a decoded lower resolution sequence.

[1]The terms *picture* and *image* are used interchangeably herein.