Temporal Resolution Enhancement in Compressed Video

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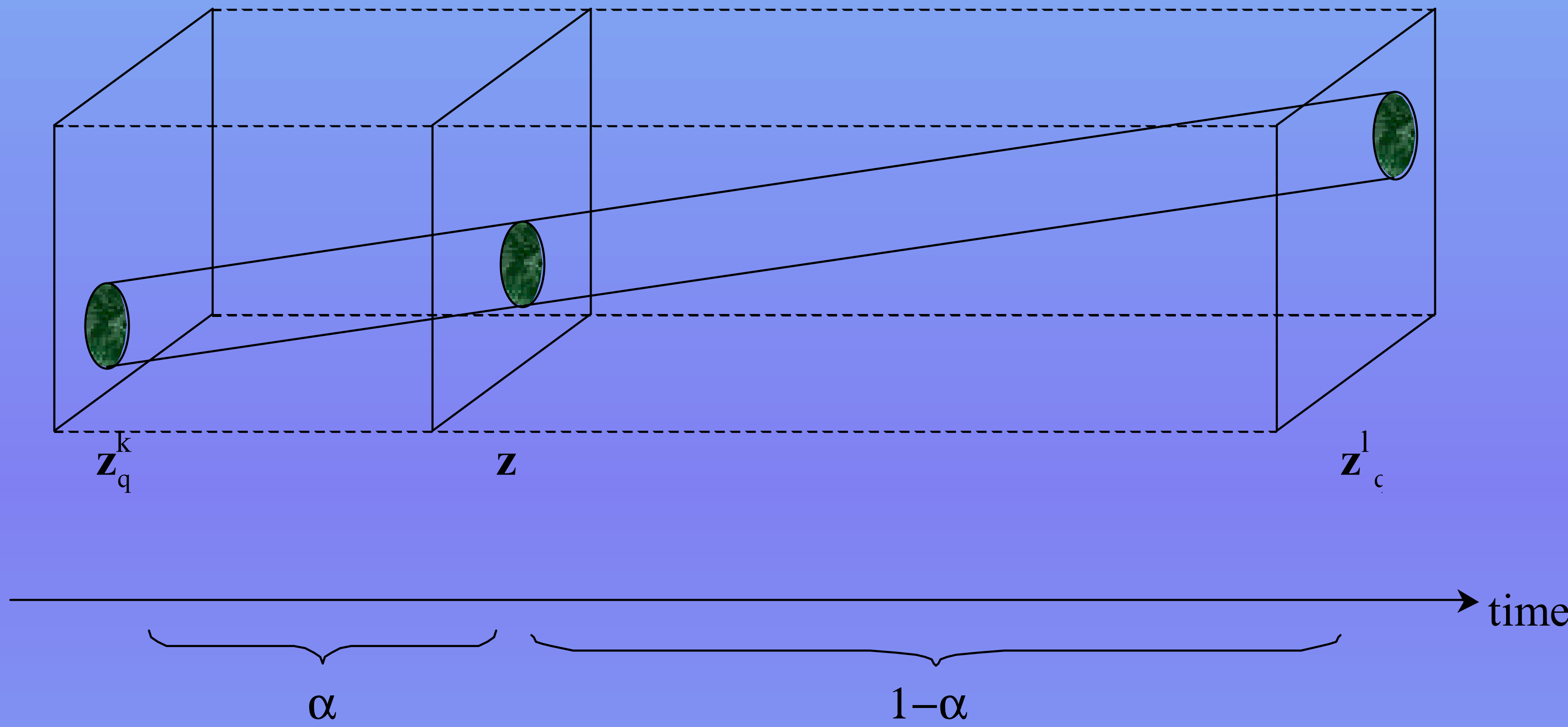
Motivation

1. Sometimes, we may want to increase video frame rate to avoid jerky, uneven motion:
   (a) Frames can be "dropped" during encoding
   (b) Might want a "slow-motion" effect
2. Frame rate is increased by inserting frames between received frames.
3. Want to prevent propagation of compression artifacts from received frames to inserted frames.

Notation:

$\mathbf{z}_q^k$	Decoded frame at time k (with quantization noise)
$\mathbf{z}_q^l$	Decoded frame at time l (with quantization noise)
$\mathbf{z}$	Frame to insert between $\mathbf{z}_q^k$ and $\mathbf{z}_q^l$



Distance between $\mathbf{z}_q^k$ and $\mathbf{z}_q^l$ is normalized to one

Assume a MAP criterion for estimation:

$$\begin{aligned}\hat{\mathbf{z}} &= \arg\max_{\mathbf{z}} p\left(\mathbf{z}|\mathbf{z}_q^k, \mathbf{z}_q^l\right) \\ &= \arg\max_{\mathbf{z}} p\left(\mathbf{z}\right) p\left(\mathbf{z}_q^k, \mathbf{z}_q^l|\mathbf{z}\right)\end{aligned}$$

$p\left(\mathbf{z}_q^k, \mathbf{z}_q^l|\mathbf{z}\right)$ relates observations to image we are estimating

$p\left(\mathbf{z}\right)$ is a prior image model that encourages smoothness

Need to relate observations $\mathbf{z}_q^k$ and $\mathbf{z}_q^l$ with frame to insert $\mathbf{z}$.

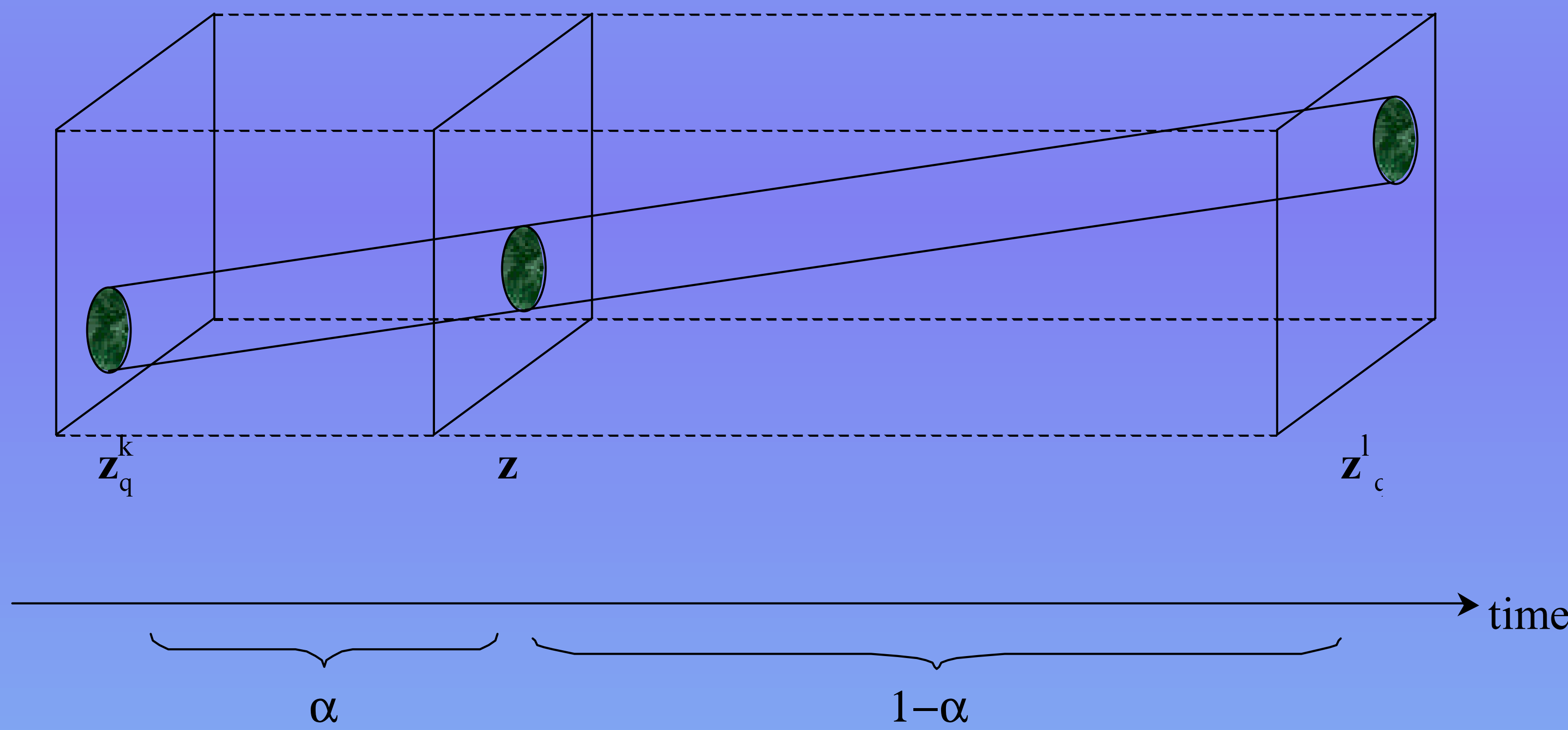
$\Longrightarrow$ start with original images (include compression noise later):

$$\mathbf{z}^k = \mathbf{A}^k \mathbf{z} + \mathbf{n}_m^k$$

$\mathbf{A}^k$ is the *motion-compensation* matrix.

$\mathbf{n}_m^k$ is the error in predicting $\mathbf{z}^k$ from $\mathbf{z}$

Motion compensation matrix from $\mathbf{z}^k$ to $\mathbf{z}$ is determined based on motion from $\mathbf{z}_q^k$ to $\mathbf{z}_q^l$ assuming constant velocity:



Now, include quantization noise in the model:

$$\begin{aligned}\mathbf{z}_q^k &= \mathbf{z}^k + \mathbf{e}_{\mathbf{z}}^k \\ &= \mathbf{A}^k\mathbf{z} + \mathbf{n}_m^k + \mathbf{e}_{\mathbf{z}}^k \\ &= \mathbf{A}^k\mathbf{z} + \mathbf{n}^k\end{aligned}$$

$\mathbf{n}^k$ is the noise (error) between $\mathbf{z}_q^k$ and its motion compensation from $\mathbf{z}$.

$$\begin{aligned}\mathbf{e}_{\mathbf{z}}^k &\Longrightarrow \text{assume Gaussian with } \mathbf{K}_{\mathbf{e}_{\mathbf{z}}}^k \\ \mathbf{n}_m^k &\Longrightarrow \text{assume Gaussian with } \mathbf{K}_m^k\end{aligned}$$

$\mathbf{e}_{\mathbf{z}}^{k}$ Quantization noise is characterized in the spatial domain by explicitly considering the quantization intervals used on DCT-domain signal. In general, *not* IID.

$\mathbf{n}_{m}^{k}$ Motion compensation noise allows high variance to be assigned to areas of low confidence—e.g., appearing or disappearing objects, lighting changes, motion estimation errors.

(more details in paper)

Assuming conditional independence

$$p\left(\mathbf{z}_q^k, \mathbf{z}_q^l|\mathbf{z}\right) = p\left(\mathbf{z}_q^k|\mathbf{z}\right) p\left(\mathbf{z}_q^l|\mathbf{z}\right)$$

where

$$p\left(\mathbf{z}_q^k|\mathbf{z}\right) = \frac{(2\pi)^{-\frac{N}{2}}}{|\mathbf{K}^k|^{\frac{1}{2}}} \exp\left\{-\frac{1}{2}(\mathbf{A}^k\mathbf{z} - \mathbf{z}_q^k)^t {\mathbf{K}^k}^{-1}(\mathbf{A}^k\mathbf{z} - \mathbf{z}_q^k)\right\}$$

and

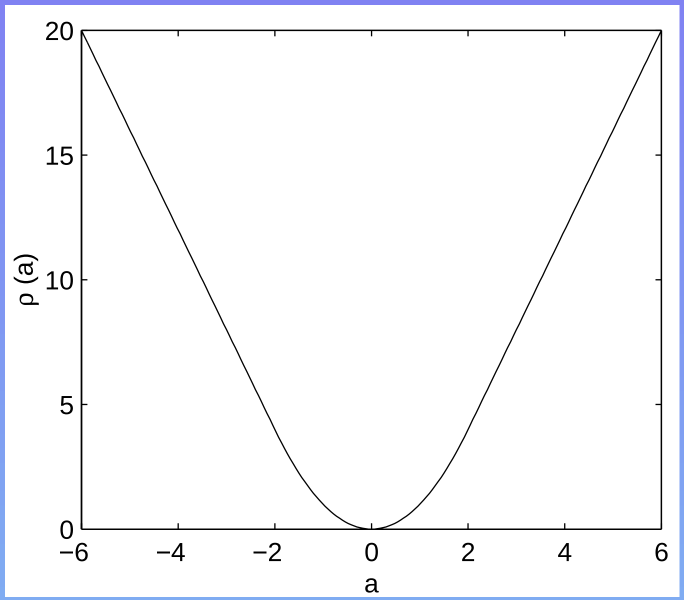
$$\mathbf{K}^k = \mathbf{K}_{\mathbf{e_z}}^k + \mathbf{K}_m^k$$

Prior Term

Huber Markov Random Field (HMRF):

$$p(\mathbf{z}) = \frac{1}{G} \exp\left\{ -\lambda_I \sum_{c \in \mathcal{C}} \rho_T\left(\mathbf{d}_c^t \mathbf{z}\right) \right\}$$

where Huber function $\rho_T(\cdot)$ looks like



Prior term has two main effects:

- Smooths artifacts such as blocking and ringing
- Fills in "gaps" in $\mathbf{z}$, to which no motion vectors from $\mathbf{z}_q^k$ or $\mathbf{z}_q^l$ point

Resulting optimization:

$$\hat{\mathbf{z}} = \arg\min_{\mathbf{z}} \left[\lambda_F r(\mathbf{z}) + s(\mathbf{z})\right]$$

where $r(\mathbf{z})$ is from the prior smoothness term, and $s(\mathbf{z})$ is from the likelihood term.

Solve using gradient descent:

Gradient is $\mathbf{g}(\mathbf{z}) = \lambda_F \nabla r(\mathbf{z}) + \nabla s(\mathbf{z})$

Estimate at k^{th} iteration is updated as

$$\mathbf{z}^{(k+1)} = \mathbf{z}^{(k)} - \tau^{(k)} \mathbf{g}\left(\mathbf{z}^{(k)}\right)$$

received frame 1: ■ □ □ □

received frame 2: □ □ □ ■

received frame 1: ■ □ □ □

inserted frame 1: □ ■ □ □

inserted frame 2: □ □ ■ □

received frame 2: □ □ □ ■

received frame 1: ■ □ □ □ □

received frame 2: □ □ □ □ ■

received frame 1: ■ □ □ □ □

inserted frame 1: □ ■ □ □ □

inserted frame 2: □ □ ■ □ □

inserted frame 3: □ □ □ ■ □

received frame 2: □ □ □ □ ■

Conclusion

Frame rate adjustment in compressed video that:

- Uses Bayesian estimation
- Explicitly considers the effect of compression noise in received video frames
- Uses prior image model to smooth compression artifacts, as well as “fill in” motion gaps in inserted frames