Chap 5. Optimization of UEP Scheme for MRF-based ISCD Decoder

\chapter{Optimization of UEP Scheme for MRF-based ISCD Decoder}

\label{chapter:optimization}

Similar to the procedure in Chapter \ref{chapter:opt-prob}, the UEP scheme in Fig.\ref{fig:uep\_encoder} is ready for construction in this chapter. Since the distortion estimator is updated in Chapter \ref{chapter:estimation} so as to adapt to the MRF based ISCD, the method used to solve the optimization problem in Chapter \ref{chapter:opt-prob} is again applied to the upgraded estimator. Because the two scenarios in Chapter \ref{chapter:opt-prob} are verified to be equivalent, only the first UEP scheme, where the encoder is given the constraint on the average transmission power and is expected to achieve the optimized received video quality, is presented in this chapter for simplicity.

In this chapter, the derivation for the UEP scheme when using MRF based ISCD is shown in Section \ref{oo:spatial}. Then, the structures of UEP scheme for three types of ISCD decoders are respectively proposed in Section \ref{oo:result}. Then, the simulated performance of the proposed UEP scheme is compared with that of the conventional EEP scheme and the results are presented in Section \ref{oo:result}. Finally, the time complexity analysis is discussed in Section \ref{oo:complexity}.

chap 5.1 UEP Scheme for ISCD Using MRF Source Decoder

\section{UEP Scheme for ISCD Using MRF Source Decoder}

\label{oo:spatial}

In order to establish the UEP scheme for MRF based ISCD, the derivation in section \ref{ccc:problem-maxpsnr} is a main reference procedure. The first step is to formulate the optimization problem by substituing (\ref{eq:distortion\_mrf}) for $\hat{D}(\gamma\_0,\mathbf{w})$ in (\ref{eq:opt\_problem\_d}).

\begin{equation}

\begin{aligned}

& \underset{\mathbf{w}\_k}{\text{minimize}} & {E[\hat{D}\_k(\gamma\_0,\mathbf{w}\_k,\mathbf{f}\_k)]} \\

& \text{subject to} & \sum\_{n=1}^{m}{w\_{k,n}} = m,

\end{aligned}

\label{eq:uep\_opt\_problem\_d}

\end{equation}

where $\gamma\_0$ is the requested average SNR and $E\_0=\gamma\_0\cdot N\_0$ is the requested average transmission energy for a bit in any bit-planes. Introducing the frame index $k$ into the optimization problem implies that (\ref{eq:uep\_opt\_problem\_d}) should execute for each frame. In order to solve the optimized weights $\textbf{w}\_k^{\ast}\equiv [w\_{k,1}^{\ast},\cdots,w\_{k,m}^{\ast}]'$ which satisfies the energy constraint, lagrange multiplier method is adopted again.

\begin{equation}

\underset{\{ \mathbf{w}\_k,\lambda \}}{\text{minimize}} \quad J = \frac{1}{4}\sum\_{n=1}^{m}{(2^{2n}BER\_{k,n})} + \lambda(\sum\_{n=1}^{m}{w\_{k,n}}-m),

\label{eq:uep\_opt\_lagrange}

\end{equation}

where $BER\_{k,n}$ is in the form of (\ref{eq:ber\_llr\_final}), and $J$ is the lagrangian cost function to be minimized. If $\textbf{w}\_k^{\ast}$ is one set of optimized solution to meet (\ref{eq:uep\_opt\_problem\_d}), there must exists at least one $\lambda^{\ast}$ such that $(\textbf{w}\_k^{\ast},\lambda^{\ast})$ is a critical point of $J$. As a result, the gradient values at this point are all 0,

\begin{equation}

\nabla\_{(\mathbf{w}\_k,\lambda)}J|\_ {\substack{\mathbf{w}\_k = \mathbf{w}\_k^{\ast} \\ \lambda = \lambda^\ast}}=\mathbf{0}.

\label{eq:uep\_lagrange\_gradient}

\end{equation}

And (\ref{eq:uep\_lagrange\_gradient}) implies the following equation system,

\begin{equation}

\left \{ \begin{array}{ll}

\begin{aligned}

\frac{\partial J}{\partial \lambda} & = & &(\sum\_{n=1}^{m}w\_{k,n})-m & = & &0 & \\

\frac{\partial J}{\partial w\_{k,n}} & = & & 2^{2n-2}\frac{\partial BER\_{k,n}}{\partial w\_{k,n}} + \lambda & = & &0 &, \quad \forall n \in \{1,\cdots,m\},

\end{aligned}

\end{array}\right. ,

\label{eq:uep\_lagrange\_derivative}

\end{equation}

where $\frac{\partial BER\_{k,n}}{\partial w\_{k,n}}$ is an important key to resolve this optimization problem since $BER\_{k,n}$ is much more complicated than $fr(\gamma\_{k,n})$. Calculating $\frac{\partial BER\_{k,n}}{\partial w\_{k,n}}$ curve versus $\gamma\_{k,n}$ is not practical while the $BER\_{k,n}$ takes not only $fr(\gamma\_{k,n})$ but also the MRF model of bit-planes into consideration.

According to (\ref{eq:ber\_llr}) and (\ref{eq:ber\_llr\_final})-(\ref{eq:ber\_llr\_ne}), $BER\_{k,n}$ can be represented by $L\_{k,n}$ which is finally derived as

\begin{equation}

L\_{k,n} = \ln{\frac{1-fr(\gamma\_{k,n})}{fr(\gamma\_{k,n})}} + \beta\_{k,n}^{[s]}\overline{N}\_{k,n}^{[s]}(1-2fr(\gamma\_{k,n}))+\beta\_{k,n}^{[t]}\overline{N}\_{k,n}^{[t]}(1-2BER\_{N\_{k,n}}),

\label{eq:L\_kn}

\end{equation}

where the notations are same with those in (\ref{eq:ber\_llr\_final}). Therefore, $\frac{\partial BER\_{k,n}}{\partial w\_{k,n}}$ can be deduced,

\begin{align}

\frac{\partial BER\_{k,n}}{\partial w\_{k,n}} = & \gamma\_0\cdot \frac{\partial}{\partial (w\_{k,n}\gamma\_0)}(\frac{1}{1+e^{L\_{k,n}}}) \nonumber \\

= & \gamma\_0\cdot\frac{-e^{L\_{k,n}}}{(1+e^{L\_{k,n}})^2}\cdot \frac{\partial L\_{k,n}}{\partial \gamma\_{k,n}} \nonumber \\

= & \gamma\_0 \cdot(\frac{1}{1+e^{L\_{k,n}}})\cdot (1-\frac{1}{1+e^{L\_{k,n}}})\cdot\frac{\partial( -L\_{k,n})}{\partial \gamma\_{k,n}} \nonumber \\

= & -\gamma\_0 BER\_{k,n} (1-BER\_{k,n})\frac{\partial L\_{k,n}}{\partial \gamma\_{k,n}},

\label{eq:ber\_derivative}

\end{align}

where $\frac{\partial L\_{k,n}}{\partial \gamma\_{k,n}}$ is further inferred as

\begin{align}

\frac{\partial L\_{k,n}}{\partial \gamma\_{k,n}} = & \frac{fr(\gamma\_{k,n})}{1-fr(\gamma\_{k,n})}\frac{-1}{(fr(\gamma\_{k,n}))^2}\cdot \frac{\partial fr(\gamma\_{k,n})}{\partial \gamma\_{k,n}} -2\beta\_{k,n}^{[s]}\overline{N}\_{k,n}^{[s]}\frac{\partial fr(\gamma\_{k,n})}{\partial \gamma\_{k,n}} + 0 \nonumber \\

= & -Df(\gamma\_{k,n})(\frac{1}{fr(\gamma\_{k,n})(1-fr(\gamma\_{k,n}))}+2\beta\_{k,n}^{[s]}\overline{N}\_{k,n}^{[s]}),

\label{eq:L\_kn\_derivative}

\end{align}

where $Df(\gamma)$ is the derivative value of $fr(\gamma)$, and it is prepared in advance as well as $fr(\gamma)$. Then, substituting (\ref{eq:L\_kn\_derivative}) into (\ref{eq:ber\_derivative}) completes the form of derivative of $BER\_{k,n}$,

\begin{equation}

\frac{\partial BER\_{k,n}}{\partial w\_{k,n}} = \gamma\_0 BER\_{k,n} (1-BER\_{k,n}) Df(\gamma\_{k,n})(\frac{1}{fr(\gamma\_{k,n})(1-fr(\gamma\_{k,n}))}+2\beta\_{k,n}^{[s]}\overline{N}\_{k,n}^{[s]}).

\label{eq:ber\_derivative\_final}

\end{equation}

In order to solve the system of (\ref{eq:uep\_lagrange\_derivative}), primal-dual iterative algorithm is applied and there are two parts to be operated in turn.

\begin{enumerate}[topsep=0pt, itemsep=0pt, label=\arabic{\*}.]

\item \texttt{fix $\lambda$ and independently solve $w\_{k,n}$:}\\

In this part, even though the derivative of $BER\_{k,n}$ is described, it is still difficult to directly solve $w\_{k,n}$ from the second equation in (\ref{eq:uep\_lagrange\_derivative}) because the required inverse function of the (\ref{eq:ber\_derivative\_final}) is complicated and nontrivial. As a consequence, newton's method should be adopted here to obtain the root $w\_{k,n}^{\ast}$ respectively for each bit-plane index $n$. That is, a function denoted by

\begin{equation}

F\_1(w\_{k,n}) = 2^{2n-2}\cdot \frac{\partial BER\_{k,n}}{\partial w\_{k,n}} + \lambda,

\label{eq:f1\_root}

\end{equation}

is constructed for each parallel pipeline with the same fixed $\lambda$. Then, the argument iteratively adjusts itself from any initial value to the root value,

\begin{equation}

w\_{k,n}^{(iter+1)} \leftarrow w\_{k,n}^{(iter)} - \alpha\_1 \cdot \frac{\Delta w \cdot F\_1(w\_{k,n}^{(iter)})}{ F\_1(w\_{k,n}^{(iter)}+\Delta w) - F\_1(w\_{k,n}^{(iter)})},

\label{eq:iter\_w\_kn}

\end{equation}

where $\alpha\_1$ is the convergent rate of this approach, $\Delta w$ is a small shift on $w\_{k,n}$, and the $w\_{k,n}^{(iter)}$ keeps updating itself until it converges to the root of (\ref{eq:f1\_root}). After the all roots $\textbf{w}\_k$ are solved independently from $m$ parallel pipelines, ( $\textbf{w}\_k$, $\lambda$) is transmitted to the next part.

\item \texttt{fix $\textbf{w}\_{k}$ and update $\lambda$:}\\

After $\textbf{w}\_k$ are all updated, this part is mainly to check whether the problem is solved and to update $\lambda$ based on newton's method. Because the roots $\textbf{w}\_k$ solved in the first part must satisfy the second equation of (\ref{eq:uep\_lagrange\_derivative}), only the first equation should be checked in this part. Set another function as

\begin{equation}

F\_2(\lambda) = (\sum\_{n=1}^{m}w\_{k,n})-m,

\end{equation}

where $w\_{k,n}$ is the root obtained in first part, and $\lambda$ is the same value with that in the first part. If $|F\_2(\lambda)|$ is smaller than some assigned threshold $\epsilon$, the primal-dual iterative algorithm is suspended and the current $\textbf{w}\_k$ is determined as the solution $\text{w}\_k^{\ast}$. Otherwise, the algorithm updates $\lambda$ once more and goes to the first part again. Besides, the $\lambda$ adjustment is

\begin{equation}

\lambda \leftarrow \lambda - \alpha\_2\cdot \frac{\Delta \lambda \cdot F\_2(\lambda)}{ F\_2(\lambda+\Delta \lambda)- F\_2(\lambda)},

\label{eq:lambda\_update}

\end{equation}

where $\alpha\_2$ is the convergent rate of this algorithm, and $\Delta \lambda$ is a small shift on $\lambda$. Fig.\ref{fig:flow\_dual} shows how the primal-dual iterative algorithm works.

\begin{figure}[!htb]

\centering

\includegraphics[width=0.8\textwidth]{fig/flow\_dual.pdf}

\caption{\label{fig:flow\_dual}A flow diagram shows how primal-dual iterative algorithm solves the formulated optimization problem in this chapter.}

\end{figure}

\end{enumerate}

After the iterative algorithm is terminated by the second part,\lambda^{\ast})$, $\textbf{E}\_s = \textbf{w}\_k^{\ast}\cdot E\_{s0}$ is therefore applied as the transmission energy allocation in Fig.\ref{fig:uep\_encoder}. In comparison with the conclusion in section \ref{ccc:problem-maxpsnr}, the updated UEP scheme becomes more general when this UEP scheme is aware of not only channel status but also redundancy between both spatial and temporal neighborhood. In the meanwhile, the proposed UEP scheme in this chapter has to recalculate the power distribution at each frame, while the UEP scheme in section \ref{ccc:problem-maxpsnr} only considers the channel condition and just calculates the distribution once. It is caused by the diversity in redundancies of different frames and the change in redundancy through the frames is unpredictable. With the more frequent computation as the penalty, the updated UEP scheme can adapt to videos with different varieties of content.

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chap 5.2 Numerical Result

\section{Numerical Result}

\label{oo:result}

In this section, the same scenario settings with those in section \ref{jj:res} are applied, including the four test sequences and the respective three types of decoders, spatial MRF based ISCD, temporal MRF based ISCD as well as 3D MRF based ISCD. In order to demonstrate the strengths of the updated UEP scheme in comparison with that of the EEP scheme, the simulation results of both UEP scheme and EEP scheme are presented together. The EEP scheme is the encoder in Fig. \ref{fig:vc\_structure} which always allocates the assigned and fixed energy $E\_{s0}$ for bits in any bit-planes. Actually, the results of EEP scheme are same with the simulation part in section \ref{jj:res}. On the other hand, the proposed UEP scheme is the encoder in Fig. \ref{fig:uep\_encoder} where the UEP block is established based on the derivation in section \ref{oo:spatial}. The different structures related to three decoders are respectively shown in following subsections.

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\subsection{UEP Scheme for ISCD with Spatial MRF Decoder}

\label{ooo:spatial}

\begin{figure}[!htb]

\makebox[\textwidth][c]{\includegraphics[width=1.15\textwidth]{fig/UEP\_scheme\_s.pdf}}

\caption{\label{fig:uep\_scheme\_s}The structure diagram of UEP scheme with respect to spatial MRF based ISCD.}

\end{figure}

In the first part, the UEP scheme with respect to the decoder using only spatial MRF based ISCD is considered. Combing the solver in Fig. \ref{fig:flow\_dual} with the spatial estimator in Fig. \ref{fig:distortion\_est\_s}, the UEP structure for spatial MRF based ISCD is depicted in Fig. \ref{fig:uep\_scheme\_s}. In Fig. \ref{fig:uep\_scheme\_s}, the proposed UEP scheme first calculates in parallel the term

\begin{equation}

E\_{k,n}\equiv e^{\beta^{[s]}\_{k,n}\overline{N}^{[s]}\_{k,n}} ,

\label{eq:e\_n\_spatial}

\end{equation}

which is related to the spatial MRF model, and then iteratively approaches the solution for energy distribution that optimizes the decoded quality. The weights solver in the structure is based on the derivation in section \ref{oo:spatial} with some simplification. According to (\ref{eq:ber\_llr\_final}) and Fig. \ref{fig:distortion\_est\_s}, $BER\_{k,n}$ in spatial ISCD can be derived as

\begin{equation}

BER\_{k,n} = \frac{fr(\gamma\_{k,n})}{fr(\gamma\_{k,n})+(1-fr(\gamma\_{k,n}))E\_{k,n}^{(1-2fr(\gamma\_{k,n}))}},

\label{eq:ber\_spatial}

\end{equation}

where $E\_{k,n}$ has been computed in (\ref{eq:e\_n\_spatial}) and fixed before the weights solver. As a consequence, (\ref{eq:ber\_derivative\_final}) can be simplified as

\begin{equation}

\frac{\partial BER\_{k,n}}{\partial w\_{k,n}} = \frac{\gamma\_0 \cdot E\_{k,n}^{(1-2fr(\gamma\_{k,n}))}\cdot Df(\gamma\_{k,n})(1+2fr(\gamma\_{k,n})(1-fr(\gamma\_{k,n}))\ln{E\_{k,n}})}{( fr(\gamma\_{k,n})+(1-fr(\gamma\_{k,n}))E\_{k,n}^{(1-2fr(\gamma\_{k,n}))})^2},

\label{eq:ber\_derivative\_spatial}

\end{equation}

where $\gamma\_0$ is the ratio of assigned average bit energy $E\_{s0}$ to channel $N\_0$, and $Df(\gamma)$ is the derivative curve of the given channel bit error rate curve $fr(\gamma)$. It is worth noting that the term $\ln{(E\_{k,n})}$ is usually near 1 and thus $2fr(\gamma\_{k,n})(1-fr(\gamma\_{k,n}))\ln{(E\_{k,n})}$ is much smaller than 1 when $fr(\gamma\_{k,n})$ is small enough. That is, (\ref{eq:ber\_derivative\_spatial}) can ignore that term and be modified as

\begin{equation}

\frac{\partial BER\_{k,n}}{\partial w\_{k,n}} \approx \frac{\gamma\_0 \cdot E\_{k,n}^{(1-2fr(\gamma\_{k,n}))}\cdot Df(\gamma\_{k,n})}{( fr(\gamma\_{k,n})+(1-fr(\gamma\_{k,n}))E\_{k,n}^{(1-2fr(\gamma\_{k,n}))})^2},

\label{eq:ber\_derivative\_spatial2}

\end{equation}

In hence, the weights solver utilizes the (\ref{eq:f1\_root}) and (\ref{eq:iter\_w\_kn}) with substitution of (\ref{eq:ber\_derivative\_spatial}) or (\ref{eq:ber\_derivative\_spatial2}) for (\ref{eq:ber\_derivative\_final}).

Following few figures show the performance comparison between the simulation results with the conventional EEP scheme, denoted by dash lines, and the proposed UEP scheme, denoted by solid lines, when using different sequences. Besides, there are two average SNR $\gamma\_0$ presented in each figure, including 0 dB, denoted by shades of blue, and 3 dB, denoted by shades of red.

\begin{figure}[!htb]

\centering

\includegraphics[width=0.9\textwidth]{fig/foreman\_intra.pdf}

\caption{\label{fig:uep\_intra\_foreman\_frame}Simulation result of EEP/ UEP scheme for spatial MRF based ISCD using "Foreman" sequence.}

\end{figure}

Fig. \ref{fig:uep\_intra\_foreman\_frame} shows the result when input sequence is "Foreman" introduced in section \ref{jj:res}. In the low SNR channel, lines in the shades of blue, the proposed UEP scheme always outperforms the EEP scheme even if there is a suddenly camera movement. The average PSNR gain is about 6.6 dB throughout the video. Besides, in the high SNR channel, lines in the shades of red, the UEP scheme is still better than EEP scheme despite of the smaller performance gain at about 3.8 dB. Therefore, the performance gain of the proposed UEP scheme decreases while the average transmission power increases. This tendency is consist with the expectation because the proposed UEP scheme should yield the more similar result with the EEP scheme in higher SNR condition, which is perceived in section \ref{ccc:res}. In addition to this phenomenon, it is noticed that the proposed UEP scheme performs better after the camera shift. The scene after the camera shift in "Foreman" sequence is less homogeneous and it is not suitable for the spatial ISCD decoding. As a consequence, the proposed UEP scheme can be aware of redundancy resident in the spatial MRF model, and thus adjusts the energy distribution among bit-planes based on detected redundancy.

\begin{figure}[!htb]

\centering

\includegraphics[width=0.9\textwidth]{fig/stefan\_intra.pdf}

\caption{\label{fig:uep\_intra\_stefan\_frame} Simulation result of EEP/ UEP scheme for spatial MRF based ISCD using "Stefan" sequence.}

\end{figure}

Fig. \ref{fig:uep\_intra\_stefan\_frame} uses the "Stefan" sequence as the test video. From the figure, it is noticed that the performance of proposed UEP scheme obviously exceeds that of EEP scheme with an average gain at 7.9 dB in 0 dB SNR and at 7.6 dB in 3 dB SNR. The improvement of the UEP scheme in this video is more remarkable than that in "Foreman" sequence although the gain still decreases with the increasing of the average SNR. The larger improvement here results from the worse performance of the original EEP scheme. In hence, there is still larger room for the enhancement through the UEP scheme when the test video is not suitable for spatial ISCD decoder.

\begin{figure}[!hb]

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\begin{subfigure}[using "Hall" sequence]{

\includegraphics[width=0.5\textwidth]{fig/hall\_intra.pdf}

\label{fig:uep\_intra\_hall\_frame}}

\end{subfigure}

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\begin{subfigure}[using "Akiyo" sequence]{

\includegraphics[width=0.5\textwidth]{fig/akiyo\_intra.pdf}

\label{fig:uep\_intra\_akiyo\_frame}}

\end{subfigure}

\caption{\label{fig: uep\_intra \_frame}Simulation result of EEP/ UEP scheme for spatial MRF based ISCD.}

\end{figure}

Fig. \ref{fig:uep\_intra\_hall\_frame} uses the "Hall" sequence as the test video, and Fig. \ref{fig:uep\_intra\_akiyo\_frame} uses the "Akiyo" sequence. Since these two sequences are more homogeneous than "Foreman" sequence, the performances of the spatial ISCD are surely better. Furthermore, the proposed UEP scheme still surpasses the EEP scheme in both 0 dB and 3 dB conditions. Nevertheless, the performance gain of the proposed UEP scheme is less effective when transmitting these two sequences. The average performance gain can be observed from figures in Fig. \ref{fig:uep\_intra}, where each figure depicts the comparison between EEP scheme and UEP scheme when using different test sequences.

\begin{figure}[!htb]

\centering

\begin{subfigure}[using "Foreman" sequence]{

\includegraphics[width=0.45\textwidth]{fig/foreman\_intra\_comp\_avg.pdf}

\label{fig:uep\_intra\_foreman}}

\end{subfigure}

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\begin{subfigure}[using "Stefan" sequence]{

\includegraphics[width=0.45\textwidth]{fig/stefan\_intra\_comp\_avg.pdf}

\label{fig:uep\_intra\_stefan}}

\end{subfigure}

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\begin{subfigure}[using "Hall" sequence]{

\includegraphics[width=0.45\textwidth]{fig/hall\_intra\_comp\_avg.pdf}

\label{fig:uep\_intra\_hall}}

\end{subfigure}

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\begin{subfigure}[using "Akiyo" sequence]{

\includegraphics[width=0.45\textwidth]{fig/akiyo\_intra\_comp\_avg.pdf}

\label{fig:uep\_intra\_akiyo}}

\end{subfigure}

\caption{\label{fig:uep\_intra}Comparison of the average PSNR versus SNR for EEP/UEP with spatial MRF based ISCD.}

\end{figure}

Therefore, it is observed that the gain in Fig. \ref{fig:uep\_intra\_hall} or Fig. \ref{fig:uep\_intra\_akiyo} is much smaller than that in Fig. \ref{fig:uep\_intra\_foreman} and Fig. \ref{fig:uep\_intra\_stefan}. It is caused by that the performance of original EEP scheme is good enough in "Hall" and "Akiyo" sequences, and thus the performance gain of the proposed UEP scheme is restricted severely when using sequences with high homogeneity.

Fig. \ref{fig:uep\_intra} demonstrates that the proposed UEP scheme indeed makes an efficient use of the limited transmission power in order to obtain the optimized decoded video quality with spatial MRF based ISCD decoder, because the proposed UEP scheme surpasses the EEP scheme in any channel condition and with four test videos. Especially in terrible channel condition like 0 dB SNR, the enhancement by the proposed UEP scheme is significant. However, the performance of the proposed UEP scheme is less effective when the original EEP scheme performs well enough, because the result of UEP scheme converges to that of EEP scheme in low bit error rate condition.

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\subsection{UEP Scheme for ISCD with Temporal MRF Decoder}

\label{ooo:temporal}

\begin{figure}[!htb]

\makebox[\textwidth][c]{\includegraphics[width=1.15\textwidth]{fig/UEP\_scheme\_t.pdf}}

\caption{\label{fig:uep\_scheme\_t}The structure diagram of UEP scheme with respect to temporal MRF based ISCD.}

\end{figure}

In the second part, the UEP scheme related to the temporal MRF based ISCD is constructed. Fig. \ref{fig:uep\_scheme\_t} shows the structure diagram of the UEP scheme and indicates the procedure of the determination of energy distribution. Similar with the first part, Fig. \ref{fig:uep\_scheme\_t} combines the temporal estimator in Fig. \ref{fig:distortion\_est\_t} and the iterative solver in Fig. \ref{fig:flow\_dual}. In the beginning, the UEP scheme calculates in parallel the term

\begin{equation}

E\_{k,n}\equiv e^{\beta^{[t]}\_{k,n}\overline{N}^{[t]}\_{k,n}\cdot (1-2 BER\_{N\_{k,n}})} ,

\label{eq:e\_n\_temporal}

\end{equation}

which is related to the temporal MRF model, and the term $BER\_{N\_{k,n}}$ represents the final estimated bit error rate in reference bit-plane $\textbf{u}\_{k',n}$. Then, the UEP scheme iteratively approaches the solution for energy distribution that optimizes the decoded quality. The temporal weights solver in the structure is based on the derivation in section \ref{oo:spatial} with some simplification. According to (\ref{eq:ber\_llr\_final}) and Fig. \ref{fig:distortion\_est\_t}, $BER\_{k,n}$ in temporal ISCD can be derived as

\begin{equation}

BER\_{k,n} = \frac{fr(\gamma\_{k,n})}{fr(\gamma\_{k,n})+(1-fr(\gamma\_{k,n}))E\_{k,n}}.

\label{eq:ber\_temporal}

\end{equation}

As a result of (\ref{eq:ber\_temporal}), (\ref{eq:ber\_derivative\_final}) can be simplified as

\begin{equation}

\frac{\partial BER\_{k,n}}{\partial w\_{k,n}} = \frac{\gamma\_0 \cdot E\_{k,n}\cdot Df(\gamma\_{k,n})}{( fr(\gamma\_{k,n})+(1-fr(\gamma\_{k,n}))E\_{k,n})^2},

\label{eq:ber\_derivative\_temporal}

\end{equation}

where $\gamma\_0$ , $Df(\gamma)$ are the same with those in (\ref{eq:ber\_derivative\_spatial}). In hence, the weights solver utilizes the (\ref{eq:f1\_root}) and (\ref{eq:iter\_w\_kn}) with substitution of (\ref{eq:ber\_derivative\_temporal}) for (\ref{eq:ber\_derivative\_final}).

Following few figures show the performance comparison between the simulation results with the conventional EEP scheme, denoted by dash lines, and the proposed UEP scheme, denoted by solid lines, when using different sequences. Besides, there are two average SNR $\gamma\_0$ presented in each figure, including 0 dB, denoted by shades of blue, and 3 dB, denoted by shades of red.

\begin{figure}[!htb]

\centering

\begin{subfigure}[using "Foreman" sequence]{

\includegraphics[width=0.5\textwidth]{fig/foreman\_inter.pdf }

\label{fig:uep\_inter\_foreman\_frame} }

\end{subfigure}

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\begin{subfigure}[using "Stefan" sequence]{

\includegraphics[width=0.5\textwidth]{fig/stefan\_inter.pdf}

\label{fig:uep\_inter\_stefan\_frame}}

\end{subfigure}

\caption{\label{fig:uep\_inter\_frame1}Simulation result of EEP/ UEP scheme for temporal MRF based ISCD.}

\end{figure}

In Fig. \ref{fig:uep\_inter\_frame1}, the simulation results of ISCD using "Foreman" and "Stefan" sequences are depicted and investigated. It is apparent that the proposed UEP scheme for temporal ISCD achieves a better performance than the EEP scheme. Additionally, due to the information propagation in temporal MRF based ISCD, the distorted information as well as the accurate information are transmitted to the next frame. As a result, the UEP scheme not only enhances the quality for one frame, but improves the accuracy of the a priori information of the next frames. The propagation of the enhanced information can be observed from the smoother variation throughout the frames in the UEP scheme than that in the EEP scheme. For example, in the "Foreman" sequence from $170^{th}$ frame to $220^{th}$ frame, there is a rapid performance drop when the EEP scheme is applied. However, in the UEP scheme, this drop is mitigated by the propagation of accurate enough information.

\begin{figure}[!hb]

\centering

\begin{subfigure}[using "Hall" sequence]{

\includegraphics[width=0.5\textwidth]{fig/hall\_inter.pdf}

\label{fig:uep\_inter\_hall\_frame}}

\end{subfigure}

%=====================

\begin{subfigure}[using "Akiyo" sequence]{

\includegraphics[width=0.5\textwidth]{fig/akiyo\_inter.pdf}

\label{fig:uep\_inter\_akiyo\_frame}}

\end{subfigure}

\caption{\label{fig:uep\_inter\_frame2}Simulation result of EEP/ UEP scheme for temporal MRF based ISCD.}

\end{figure}

On the other hand, Fig. \ref{fig:uep\_inter\_frame2} depicts the simulation results when using "Hall" and "Akiyo" sequences. In Fig. \ref{fig:uep\_inter\_frame2}, it is noticed that the performance gain is not as good as that in Fig. \ref{fig:uep\_inter\_frame1} though the UEP scheme still surpasses the EEP scheme. In 0 dB channel, both Fig.\ref{fig:uep\_inter\_hall\_frame} and Fig. \ref{fig:uep\_inter\_akiyo\_frame} show that the proposed UEP scheme can still exceed the performance of EEP scheme with a gain at 2 dB. Besides, the effect of mitigated drop is also observed in this SNR condition. However, in 3 dB channel, the performance of the original EEP scheme already achieves high quality at 58 dB, and thus the performance of the proposed UEP scheme is similar with that of the EEP scheme. The effort of the UEP scheme is just to stabilize the video quality in a smaller range and smoothen the distortion varying. By allocating more energy for the more important bit-planes, the decoder has a better ability to tolerate the disturbance from the noise. Therefore, the decoded quality can be steady at such a high quality. According to (\ref{eq:psnr}), the expected distortion for $PSNR=58 dB$ should be less than 0.1 $\text{pixel}^2$ in term of average square error.

\begin{figure}[!htb]

\centering

\begin{subfigure}[using "Foremane" sequence]{

\includegraphics[width=0.45\textwidth]{fig/foreman\_inter\_comp\_avg.pdf}

\label{fig:uep\_inter\_foreman}}

\end{subfigure}

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\begin{subfigure}[using "Stefan" sequence]{

\includegraphics[width=0.45\textwidth]{fig/stefan\_inter\_comp\_avg.pdf}

\label{fig:uep\_inter\_stefan}}

\end{subfigure}

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\begin{subfigure}[using "Hall" sequence]{

\includegraphics[width=0.45\textwidth]{fig/hall\_inter\_comp\_avg.pdf}

\label{fig:uep\_inter\_hall}}

\end{subfigure}

\quad

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\begin{subfigure}[using "Akiyo" sequence]{

\includegraphics[width=0.45\textwidth]{fig/akiyo\_inter\_comp\_avg.pdf}

\label{fig:uep\_inter\_akiyo}}

\end{subfigure}

\caption{\label{fig:uep\_inter}Comparison of the average PSNR versus SNR for EEP/UEP with temporal MRF based ISCD.}

\end{figure}

Fig. \ref{fig:uep\_inter} shows the comparison of simulated performance of ISCD based on temporal MRF model versus four SNR conditions. In comparison with Fig. \ref{fig:uep\_intra}, the PSNR gain of temporal UEP scheme is less evident than that of spatial UEP scheme except for the result of "Stefan". Especially for "Hall" and "Akiyo" sequences, the proposed UEP scheme cannot effectively enhance the performance when applying temporal MRF-based ISCD. It is caused by the reason that the proposed distortion estimator for temporal ISCD is not precise enough, especially when the test video contains rich temporal redundancy. The comparison of the simulated result and the estimated result in Fig.\ref{fig:akiyo\_inter\_est} shows that the estimated distortion still has a certain and perceptible amount of error with the simulated distortion. This error would increases in the high SNR channel, and thus the inferred UEP scheme based on this incomplete estimator obtains the solution with some misestimation. And Fig.\ref{fig:uep\_inter} just demonstrates the cheap performance gain which results from the mentioned misestimation in inference of the proposed temporal UEP scheme.

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\subsection{UEP scheme for 3D-MRF based ISCD}

\label{ooo:3d}

\begin{figure}[!htb]

\makebox[\textwidth][c]{\includegraphics[width=1.15\textwidth]{fig/UEP\_scheme\_3d.pdf}}

\caption{\label{fig:uep\_scheme\_3d}The structure diagram of UEP scheme with respect to 3D MRF based ISCD.}

\end{figure}

In the last part, the UEP scheme with respect to the 3D MRF based ISCD is constructed according to the final derivation in (\ref{eq:ber\_derivative\_final}) where $BER\_{k,n}$ is presented in (\ref{eq:ber\_llr\_final})-(\ref{eq:ber\_llr\_ne}). Different from the structures in previous two parts, the distortion estimation not only depends on the temporal redundancy but also spatial redundancy. As a result, the derivation of the distortion estimation cannot be further simplified. The structure diagram of the proposed UEP scheme for the 3D MRF based ISCD is shown in Fig. \ref{fig:uep\_scheme\_3d} where

\begin{equation}

E\_{k,n}\equiv e^{\beta^{[s]}\_{k,n}\overline{N}^{[s]}\_{k,n} + \beta^{[t]}\_{k,n}\overline{N}^{[t]}\_{k,n}\cdot (1-2 BER\_{N\_{k,n}})} .

\label{eq:e\_n\_3d}

\end{equation}

Again, based on the structure in Fig. \ref{fig:uep\_scheme\_3d}, following charts of simulation results use the same notations with those in the previous sections.

\begin{figure}[!htb]

\centering

\begin{subfigure}[using "Foreman" sequence]{

\includegraphics[width=0.5\textwidth]{fig/foreman\_3d.pdf }

\label{fig:uep\_3d\_foreman\_frame} }

\end{subfigure}

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\begin{subfigure}[using "Stefan" sequence]{

\includegraphics[width=0.5\textwidth]{fig/stefan\_3d.pdf}

\label{fig:uep\_3d\_stefan\_frame}}

\end{subfigure}

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\begin{subfigure}[using "Hall" sequence]{

\includegraphics[width=0.5\textwidth]{fig/hall\_3d.pdf}

\label{fig:uep\_3d\_hall\_frame}}

\end{subfigure}

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\begin{subfigure}[using "Akiyo" sequence]{

\includegraphics[width=0.5\textwidth]{fig/akiyo\_3d.pdf}

\label{fig:uep\_3d\_akiyo\_frame}}

\end{subfigure}

\caption{\label{fig:uep\_3d\_frame}Simulation result of EEP/ UEP scheme for 3D MRF based ISCD.}

\end{figure}

In Fig. \ref{fig:uep\_3d\_frame}, it is observed that performance of the proposed UEP scheme using “Foreman” and “Stefan” sequences clearly surpasses that of EEP scheme. The proposed UEP scheme can improve the decoded quality no matter in any channel condition when using these two footages. Besides, the effects indicated in the first part, maintaining a video quality and reducing the impact of the quality drop, can also be detected from the figures in Fig.\ref{fig:uep\_3d\_foreman\_frame} and Fig. \ref{fig:uep\_3d\_stefan\_frame}. As for Fig. \ref{fig:uep\_3d\_hall\_frame} and Fig. \ref{fig:uep\_3d\_akiyo\_frame}, although the decoded quality gain when using “Hall” and “Akiyo” sequences is not obvious, the proposed UEP scheme still provides the system the ability to mitigate the quality varying. Furthermore, the overall average PSNR of the proposed UEP scheme is also higher than that of EEP scheme as shown in Fig. \ref{fig:uep\_3d}.

\begin{figure}[!htb]

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\begin{subfigure}[using "Foremane" sequence]{

\includegraphics[width=0.45\textwidth]{fig/foreman\_3d\_comp\_avg.pdf}

\label{fig:uep\_3d\_foreman}}

\end{subfigure}

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\begin{subfigure}[using "Stefan" sequence]{

\includegraphics[width=0.45\textwidth]{fig/stefan\_3d\_comp\_avg.pdf}

\label{fig:uep\_3d\_stefan}}

\end{subfigure}

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\begin{subfigure}[using "Hall" sequence]{

\includegraphics[width=0.45\textwidth]{fig/hall\_3d\_comp\_avg.pdf}

\label{fig:uep\_3d\_hall}}

\end{subfigure}

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\begin{subfigure}[using "Akiyo" sequence]{

\includegraphics[width=0.45\textwidth]{fig/akiyo\_3d\_comp\_avg.pdf}

\label{fig:uep\_3d\_akiyo}}

\end{subfigure}

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\caption{\label{fig:uep\_3d}Comparison of the average PSNR versus SNR for EEP/UEP with 3D MRF based ISCD.}

\end{figure}

Fig. \ref{fig:uep\_3d} depicts the average PSNR performance when using different sequences under a variety of channel conditions. It is worth noting that the original performance of the 3D MRF based ISCD with EEP scheme in encoder is actually remarkable already. Thus, the propose UEP scheme is verified effective since it can further enhance the decoding quality. Additionally, the simulation results also confirm the ability of the proposed UEP scheme to maintain the video quality and to mitigate quality rapid varying.

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While the performance of our proposed UEP scheme is remarkable, the complexity of the system turns into the next concern. Therefore, time complexity of the spatial UEP scheme operation is analyzed through recording the simulation CPU time consumption for spatial UEP scheme with sequences in different resolutions. The simulation is executed on a PC in 64 bit Windows 7, Intel i7 CPU, 8 cores and 12G RAM. The analysis result is depicted in Fig. \ref{fig:complexity}. The x-axis $N$ is the number of total pixels in a frame, that is the product of the width and height in resolution. Four resolutions are tested in this analysis including $352\times288$ (CIF), $832\times 480$ (4CIF), $1280\times 720$ (HDTV) and $1920\times 1080$ (Full HD).

\begin{figure}[!htb]

\includegraphics[width=\textwidth]{fig/time\_complexity.pdf}

\caption{\label{fig:complexity}The measured time complexity shows the proposed UEP scheme is {\textbf O}(N).}

\end{figure}

From the result shown in Fig. \ref{fig:complexity}, it is noticed that the tendency is approximately linear and thus the thin black line denotes the linear trendline. As a result, the time usage of spatial UEP is linear to $N$, that is the time complexity of UEP is ${\textbf O}(N)$. Such complexity causes less loading to the encoder system which does not implement video compression. Even the Full HD video only takes about $0.4$ second for each frame to execute the proposed spatial UEP computation.

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