Joint Source-Channel Coding for Image Transmission over Flat Fading Channels

*Presentation at Tandberg*

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6/6 - 2007
Outline

- Motivation
- Proposed system
  - Source
  - Channel
  - Combination
- Results
- Conclusion
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Joint source-channel coding

- Claude Shannon proved that separate design of source and channel codes can give an overall optimal system.

- Infinite complexity and delay.

- A joint approach might give a better overall system performance when delay and complexity are considered.

- Joint source-channel coding (JSCC) takes information about both source and channel into account. Example: Unequal error protection.
Multimedia wireless transmission

Digital vs analog:

- Analog systems:
  - Robust, no clear breakdown. Can track channel quality.
  - Inefficient use of bandwidth. Low compression.

- Digital systems:
  - Compression possible, use little bandwidth.
  - Can experience sharp breakdown.

- Our goal:
  - To join the best of the two worlds.
Impact of errors
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Proposed system

- Fading channel, source prepared for transmission.
- Map source samples into channel space through nonlinear mappings.
- Channel samples sent as time discrete amplitude continuous PAM symbols.
Proposed system

- Fading channel, source prepared for transmission.
- Map source samples into channel space through nonlinear mappings.
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Filter bank structure

- Image is decorrelated by using a *tree structured filter bank*.
- Eight uniform bands.
- Lowpass band further filtered using a two band filter bank in a tree structure, *dyadic splitting*.
- Filter bank is *maximally decimated*.
- Different *subbands* organized as shown (top), low frequency bands are placed to the top left.
Description of filtered image

- Mean of lowpass-lowpass band is removed to reduce power.
- Estimate variance from blocks of size $8 \times 8$ from filtered image, resulting in variances of $N$ blocks.
- Average rate given by

$$ R = \frac{1}{N} \sum_{n=0}^{N-1} \frac{1}{2} \log_2 \left( \frac{\sigma_{X_n}^2}{\sigma_{D_n}^2} \right) \text{ bits/source sample,} \quad (1) $$

where

$$ \sigma_{D_n}^2 = \min(\mu, \sigma_{X_n}^2), \quad (2) $$

and $\mu$ is the distortion-level for sources with $\sigma_{X_n}^2 \geq \mu$. 
Proposed system - Channel
Fading channels

- Transmitted signal can experience reflection, scattering and diffraction due to obstacles such as buildings, terrain etc.

- Signal components might be delayed, attenuated and shifted in phase at receiver. Constructive/destructive components $\Rightarrow$ fluctuations in received power.
Fading channels cont’d

- **Flat** fading:
  - All frequency components attenuated equally within a band.

- **Slow** fading:
  - Channel constant during the transmission of a codeword.

Usual to write received signal $y(k)$ as

$$y(k) = \sqrt{\alpha(k)} s(k) + n(k),$$

where $\sqrt{\alpha(k)}$ is the ergodic and stationary channel gain, $s(k)$ is the sent signal and $n(k)$ is AWGN.
Fading channels cont’d

- Instantaneous channel signal-to-noise ratio (CSNR), $\gamma(k)$, given by

$$
\gamma(k) = \frac{\bar{\sigma}_S^2 \alpha(k)}{\sigma_N^2},
$$

where $\bar{\sigma}_S^2$ is transmitted power and $\sigma_N^2$ is power of inband AWGN.

- Assume $E[\alpha] = 1$. The expected CSNR, $\bar{\gamma}$, becomes

$$
\bar{\gamma} = \frac{\bar{\sigma}_S^2}{\sigma_N^2}.
$$
Fading channels cont’d

\[ \bar{\gamma} = 20 \text{ dB}. \]
Technique to increase rate

- Increase rate by splitting CSNR range into regions and use separate settings within each region.
- Traditional systems use lower threshold in a region as value to code for.
- Can be increased with power allocation.
- Robustness of mappings means that design is more free.
Nonlinear mappings
Mapping example

- Shannon, Kotel’nikov
- Optimized for a CSNR
- Limited set

\[ \hat{r}_j \in \{0, \frac{1}{4}, \frac{1}{2}, \frac{2}{3}, 1, 2\} \]

- Give different protection
- Rate given in channel/source samples
Robustness

\[ \hat{r} = \frac{1}{2} \]

\[ \hat{r} = 2.0 \]

- Figures optimized for \( \gamma = \{10, 20, 30\} \) dB.
Choosing mapping rate

- Instantaneous capacity of fading channel:
  \[ C = \frac{1}{2} \log_2 (1 + \gamma(k)) \text{ bits/channel symbol} \]

- Rate distortion function for white Gaussian source:
  \[ R = \begin{cases} 
    \frac{1}{2} \log_2 \left( \frac{\sigma_X^2}{\sigma_D^2} \right), & \text{if } 0 \leq \sigma_D^2 \leq \sigma_X^2 \\
    0, & \text{if } \sigma_D^2 > \sigma_X^2, 
  \end{cases} \]
  in bits/source sample.
Choosing mapping rate cont’d

- Combine channel capacity and rate distortion:

\[ r_{n,m} = \frac{\log_2 \left( \frac{\sigma_{Xn}^2}{\sigma_D^2} \right)}{\log_2 (1 + \gamma_{C_m})} \] channel/source sample.

⇒ optimal performance theoretically attainable (OPTA).

- Performance of implemented mappings must be considered in practice.

- Can choose to compensate for under/over protection by minimizing total distortion.

⇒ Each block is coded for certain CSNR.
Preallocation
Preallocation

Preallocate blocks to states and mapping rates based on assumed channel statistics.

Can plan transmission time(rate) and power.

Changes has to be made on the fly if assumed channel does not match seen.
Adapt to channel gain

- Assume that complete channel state information (CSI) is available.
- Possible to invert channel gain within each channel region to maintain fixed CSNR at receiver.
  - Requires much CSI.
- Rely on robustness of mappings:
  - No gain adaptation.
  - Use single factor per channel region.
- Receiver can partly compensate for channel gain mismatch.
Theoretical system

Combine channel capacity with estimated rate distortion for given average number of channel samples/source samples, \( r_{\text{avg}} \),

\[
r_{\text{avg}} C(\bar{\gamma}) = R(\mu).
\]

- Estimate the performance of a system with infinite number of ideal mappings for any given image by adding resulting distortion, \( \mu \), on image blocks.
- Estimate the performance of a system with a given set of mappings with chosen performance.
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# Results, parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>$f_c$</td>
<td>2.0 GHz</td>
</tr>
<tr>
<td>Symbol duration</td>
<td>$T_s$</td>
<td>4 µs</td>
</tr>
<tr>
<td>Doppler shift</td>
<td>$f_m$</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Statistical sample size</td>
<td>$D$</td>
<td>2000</td>
</tr>
<tr>
<td>Mobile velocity</td>
<td>$v$</td>
<td>15 m/s</td>
</tr>
</tbody>
</table>
Results, robustness

No channel information at either end.

\[ \tilde{\gamma} = 15 \text{ dB}, \ r_{\text{avg}} = 0.5. \]
Results, spread

- “Goldhill”
- $r_{\text{avg}} = \{0.5(\text{blue}), 0.1(\text{green})\}$
- Four regions with transmission + Outage
Results, preallocation

- Preallocation and example of received SNR
- Four regions + outage, $\bar{\gamma} = 6$ dB, $r_{avg} = 0.5$. 
Results, preallocation

- Preallocation and example of received SNR, each block coded for given CSNR.

- Four regions + outage, $\bar{\gamma} = 6$ dB, $r_{avg} = 0.5$. 
Results, gain adaptation

No Region

- Bridge
- CSNR per block (solid)
Results, Channel regions

- x: 1+outage, CSNR per block (solid)
- o: 2+outage
- -: 4+outage
Results, PSNR distribution

\[ \bar{\gamma} = 6 \text{ dB}. \]

- Lena
- Quality of received image will be spread due to limited number of transmitted symbols.
Image examples

- $r_{\text{avg}} = 0.1, \bar{\gamma} = 10 \text{ dB}$.

- Reference system: JPEG2000 coded for bits/pixel $R_s$, given by

$$R_s = r_{\text{avg}} R_c,$$

where $R_c$ is the rate of the channel system for a given $\bar{\gamma}$.

- Reference systems:
  1. Using set of AWGN capacity achieving codes, infinite power adjustment.
  2. Using Turbo Coded Modulation (TuCM). Varying transmit power, constellation size and turbo code.
Image examples

P: PSNR = 31.1 dB

1: PSNR = 31.5 dB

2: PSNR = 30.4 dB
Image examples

P: PSNR = 24.0 dB

1: PSNR = 23.7 dB

2: PSNR = 23.1 dB
Conclusion

- Presented a system that transmits images over a wireless channel using nonlinear mappings.
- Robust, with graceful degradation. Can track channel changes.
- Little loss in performance when reducing amount of channel information.
Questions?