AnalogCast: Full Linear Coding and Pseudo Analog Transmission for Satellite Remote-sensing Images

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ABSTRACT:

In this paper, we propose a novel image coding and transmission scheme called AnalogCast, which is a pseudo analog coding system for transmitting satellite remote-sensing images to large number of receivers. AnalogCast follows the idea originally developed for SoftCast [1-3] but with two special techniques, scale factor estimate based on L-shaped chunk division and scale factor fix curve-fitting model, so that there is no need to transmit side information as is required for SoftCast [1-3]. This improvement can get better mobility, less bandwidth and computational budget than SoftCast [1-3]. For robustness, AnalogCast adopts a mode of GOP (Group of Pictures) interweave structure to smooth image quality and improve perceptual quality when packet loss happens. Experimental results show that the proposed method can work well in low SNR condition in -7dB to 4dB where SoftCast system and JPEG2000 system fall into "cliff effect". And in high SNR condition, our proposed method works even better than SoftCast system at SNR 1.5~3dB and a gain of 1~10dB over JPEG2000 with forward error correction. For robustness, the AnalogCast works better than SoftCast at SNR 8dB when the burst packet loss rate is higher than 35%. And the scheme gets better perceptual quality under packet loss.

Index Terms—Image broadcasting, satellite images, analog coding, GoP interweave, fix model.

1. INTRODCTION

Existing satellite remote-sensing image transmission system faces many problems [4]. Frist, with the improvement of the resolution of the satellite image, satellite transmission bandwidth resources are becoming a constraint. Second, system transfers data from satellite to ground station and then uses ground network to send data to user, so the user can't have the image at real-time. Third, for users at the remote area which is lack of ground network, the system can't support the service. To solve the last problem, we can use the satellite to broadcast image directly to the users.

Conventional video/image broadcasting system needs to choose the bit-rate to encode the source and then transfer the encoded data through the digital channel. When the channel conditions are worse than the pre-defined threshold, the image quality will fall rapidly, and image quality will not increase even if the condition is better than the threshold. This is so called "cliff effect". To avoid this effect, the system must estimate channel condition accurately. However, channel condition may vary drastically and unpredictably, especially in wireless communication scenarios.

Recently, a scheme called SoftCast [1-3] was proposed for wireless video broadcasting. SoftCast has four advantages compared with the conventional video/image transmission system. First, because of the use of analog channel coding it fits different channel conditions well. The receiver which has better channel condition gets the better image quality. Second, it uses limited channel bandwidth to get the better robustness. Third, The SoftCast can work well when packect loss rate is less than 10%. Fourth, SoftCast's algorithm is simpler than the conventional system, its channel coding doesn't need to do interweave operation, FEC coding and QPSK/QAM modulation.

But SoftCast remains still much more room for improvements. LineCast [4] uses line by line coding and transmission to get the low encoder complexity, better performance, low memory requirement and low delay. G-cast [6] uses base layer to send the low-frequency components of image and enhancement layer to send the gradient information. G-cast has better performance than SoftCast and its perceptual quality is better than SoftCast when their PSNR are kept the same. But none of them consider the side information transmission's disadvantages and improve the system robustness. And these are the main efforts of our work.

In this paper, we improve SoftCast system performance in three ways:

1) System uses estimated scale factors based on L-shaped chunk division to get better mobility, less bandwidth cost and computational budget than the original SoftCast.

2) System uses GOP (group of pictures) interweave to make each image quality smooth and to improve perceptual quality under packet loss.

3) System uses scale factor fix curve-fitting model to improve the image quality when channel condition is poor or when packet loss happens.

The rest of the paper is organized as follows. **Section II** describes the proposed AnalogCast with detailed explanation of each component. **Section III** describes the evaluation environment. **Section IV** analyzes the experimental results of AnalogCast, SoftCast and JPEG2000. **Section V** concludes the paper.

2. ANALOGCAST'S ENCODER AND DECODER

Fig.1 shows the framework of our proposed scheme. For sender, the input image is first de-correlated by 2D-DCT. Then it scales the DCT components using scale factors based on L-shape chunk division. To protect the packet loss, we use Walsh-Hardmard transform to whiten the data and use GOP interweave to disperse the hurt of packet loss. Then we modulate the data to a denser constellation (e.g 64k-QAM). For receiver, after demodulation and inverse Walsh-Hardmard transform, we estimate the scale factors of the received data and estimate fix factors by the scale factor fix using curve-fitting model. Finally we recover the data by 2D-IDCT.

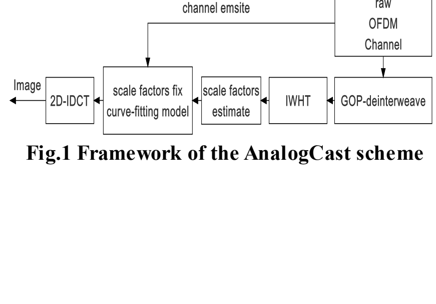

Fig.1 Framework of the AnalogCast scheme

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2.1. Decorrelation and Data Scaling: First stage is decorrelation. We choose the frame-decorrelation transform - DCT as in SoftCast. There are two advantages: 1) It redistributes the energy (also called information) to a few components; 2) It de-correlates the image signal since it projects it on an orthogonal basis.

For instance, an 1024×1024 image is first shifted down by 2^{b-1} (to renormalize the signal), the b is the pixel sampling depth. After shift, do the 2D-DCT to the image. It is formulated as follows:

$$y = 2\mathrm{D} - \mathrm{DCT}(x - 2^{b-1}) \quad (1)$$

Now we propose a scale factor estimate based on L-shaped chunk division to do data scaling. First we discuss the chunk derivation. The SoftCast uses equal chunk division which is proved to be an inefficient way [5,13]. Our algorithm is based on the L-shaped chunk division. For every image we use the same L-shaped chunk boundary and all the receivers are aware of this arrangement in advance. The L-shaped chunk division shown as **Fig2**.

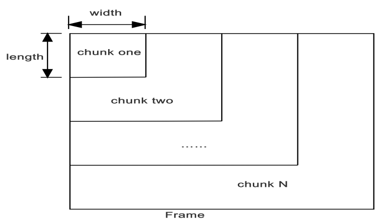


Fig2 Chunk division

We choose to divide the whole frame into chunks (In this paper, we divide the whole frame into 1024 chunks and each chunk has the same width and length). We calculate the DCT component variance λ_i of each chunk using **eq2**. Then we get the scale factors using control transmission power parameter P (all receivers know that) by $g_i = P.\lambda_i^{-1/4}$. The $u_{i,j}$ can be derived by **eq3** to protect error [11-12] and it is the data after scale to protect Gaussian noise.

$$\lambda_i = \frac{1}{chunknum} \sum_{k=1}^{chunknum} {y_{i,k}}^2 \quad (2)$$

$$u_{i,j} = g_i y_{i,j} \quad (3)$$

2.2. Whitening and Interweave: Then we must put those data into packets. But we can't put the whole frame directly into the packets. If system suffers packet loss, the empty holes will be generated in the image. So we must keep every packet to have the same information (also be called energy). To solve this problem, use the Hadamard matrix to whiten the energy of each component as follows:

$$v = HuH^T \quad (4)$$

After whitening, we choose inter-interweave (if a system requires the low decoding delay, this step can be skipped) and intra-interweave to improve image quality when packet loss happens. As **Fig3** shows, we design a mode of GOP interweave. For intra-interweave, we define four kinds of pixels as **Fig3(a)** by their locations in the image. Then use random reordering (all the receivers are aware of this arrangement in advance) for each kind of pixel as **Fig3(b)** and reshape the image data like **Fig3(c)** to reduce the influence of location information. For inter- interweave, we define 32 frame reshaped data as a GOP. Then we packetize the layer of GOP as **Fig3(d)** into one packet.

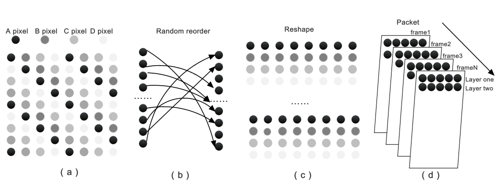


Fig3 GOP Interweave

2.3. Decoder: As the receiver, it receives all packets and de-interweaves them into the GOP. We re-write the GOP as:

$$\hat{v} = HuH^T + n \quad (5)$$

Where the $\hat{v}$ is the matrix of the received values, The H is Hadamard [9] matrix known to the receiver. So the decoder can get the estimation of $u_{i,j}$ by $\hat{u} = H^{-1}\hat{v}(H^T)^{-1}$. Different from SoftCast, we don't send the scale factors as side information to the receiver. So we must use the received data to estimate and recover the scale factors. We calculate the variance for each chunk $\hat{\mu}$ as follows:

$$\hat{\mu}_i = \frac{1}{chunknum} \sum_{k=1}^{chunknum} {\hat{u}_{i,k}}^2 \quad (6)$$

Because of $\hat{u}^2 = \hat{g}^2\hat{y}^2 = P^2.\hat{\lambda}^{-1/2}.\hat{y}^2$ and $\hat{\lambda}_i = \frac{1}{chunknum} \sum_{k=1}^{chunknum} {\hat{y}_{i,k}}^2$, we can get **eq7** and **eq8**.

$$\hat{\mu}_i = P^2.{\hat{\lambda}_i}^{1/2} \quad (7)$$

$$\hat{g}_i = P^2.{\hat{\mu}_i}^{-1/2} \quad (8)$$

Although we get the estimate of scale factors, when channel condition is poor or packet loss happens, the estimation will be inaccurate. For channel noise, it comes from the inaccurate estimate of chunk variance. As $\hat{\mu}_i = \frac{1}{chunknum} \sum_{k=1}^{chunknum} (u_{i,k} + n_{i,k})^2$ is shown, inaccurate estimate of chunk variance means that $\hat{g}_i$ is inaccurate. For packet loss, it comes from the energy (or so-called information) loss. The packet loss will cause the chunk variance estimate to reduce, so the scale factor $\hat{g}_i$ value becomes larger.

We use a scale factor fix curve-fitting model to fix the error caused by channel noise and packet loss. We decide the fix factor as α_i shown in **eq10** to fix the inaccurate estimate by channel noise and β_i shown in **eq9** to fix the inaccurate estimate by packet loss.

$$\hat{\beta}_i \begin{cases} \left(1 - C1.2^{(1-PLR)}.PLR\right), i = 1 \\ \left(1 - C2.\,2^{(1-PLR)}.PLR\right), i = 2,3 \\ \left(1 - C3.2^{(1-PLR)}.PLR\right), i > 3 \end{cases} \quad (9)$$

$$\hat{\alpha}_i \begin{cases} = \frac{C4}{mean_L}.e^{\left(\frac{-(C5snr+C6)}{mean_L}\right)}.i^{\left(\frac{(C7snr+C8)}{mean_L}\right)} + 1 \\ \quad i = 1,2,\ldots,N \\ = \frac{C4}{mean_L}.e^{\left(\frac{-(C5snr+C6)}{mean_L}\right)}.N^{\left(\frac{(C7snr+C8)}{mean_L}\right)} + 1 \\ \quad i = N+1,\ldots,M \end{cases} \quad (10)$$

The M is the number of chunks of AnalogCast and the N is a number which is *round*(0.85M)<N<M.

The parameter $mean_L$ describes the energy compaction degree. As shown in **eq11**, the δ_i is the average amplitude of each chunk. The $mean_L$ is equal to chunk 1 to 20's δ_i divided by chunk 21 to 40's δ_i as shown in **eq12**. The higher value of $mean_L$ implies the higher energy compaction.

$$\hat{\delta}_i = \frac{1}{chunknum} \sum_{k=1}^{chunknum} ABS(\hat{u}_{i,k}) \quad (11)$$

$$mean_L = \frac{\sum_{k=1}^{20} \hat{\delta}_k}{\sum_{k=21}^{40} \hat{\delta}_k} \quad (12)$$

After extensive test for 1024×1024 satellite images, we choose parameter group $C1 = 1$, $C2 = 0.9$, $C3 = 0.8$, $C4 = 10$, $C5 = 1.36315$, $C6 = 31.2$, $C7 = 0.115$, $C8 = 4.656$. And our chunk number is 1024 and for N we choose 900. So the fix factors can be shown as **eq13** and **eq14**. To use the model, the receiver only needs to know the channel condition SNR, packet loss rate and calculate the energy compaction degree $mean_L$.

$$\hat{\beta}_i\begin{cases}\left(1-2^{(1-PLR)}.PLR\right), i=1\\ \left(1-0.9.2^{(1-PLR)}.PLR\right), i=2,3\\ \left(1-0.8.2^{(1-PLR)}.PLR\right), i>3\end{cases} \tag{13}$$

$$\hat{\alpha}_i\begin{cases}=\frac{10}{mean_L}.e^{\left(\frac{-(1.36315snr+31.2)}{mean_L}\right)}.i^{\left(\frac{(0.1155snr+4.656)}{mean_L}\right)}+1\\ \qquad i=1,2,\ldots,\ 900\\ =\frac{10}{mean_L}.e^{\left(\frac{-(1.36315snr+31.2)}{mean_L}\right)}.900^{\left(\frac{(0.1155snr+4.656)}{mean_L}\right)}+1\\ \qquad i=901,,\ldots,\ 1024\end{cases} \tag{14}$$

After getting the fix factor, we can get the DCT components y by **eq15**.

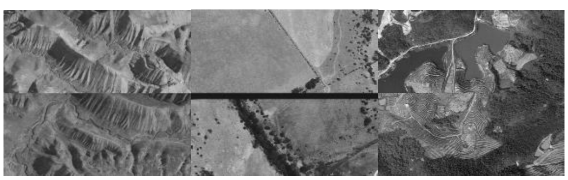
$$\hat{y}_{i,j}=P^2.\hat{\alpha}_i.\hat{\beta}_i.\hat{\mu}_i^{-1/2}.\hat{u}_{i,j} \tag{15}$$

Then using the 2D-IDCT we can get the estimated image pixels by $\hat{x}=2D-IDCT(\hat{y})+2^{b-1}$.

3. EVALUATION ENVIRONMENT

We have implemented a prototype of AnalogCast which is evaluated in comparison against SoftCast and JPEG2000 [10] using Matlab R2010. For SoftCast, we implement the system as that in [3]. For JPEG2000, the reference software Jasper [7] is used. Different combinations of FEC rates are used whose inner code is convolutional code and outer code is Reed-Solomon code.

Test Source: we choose three satellite images shown as **Fig4**. The image1 has fewer details, the image2 has medium details and image3 has the most details.



(a) (b) (c)

Fig.4 Test satellite image: (a) Image 1. (b) Image 2. (c) Image 3.

Channel conditions: Considering the satellite communication broadcasting channel, we use the additive white Gaussian noise to simulate the satellite channel. The measurement SNRs span from -7 to 27 dB. All schemes are tested by the same SNR.

Carrier Frequency offset and Sampling Frequency offset: the carrier frequency is Ku band which is 20GHz. Both carrier frequency offset and sampling frequency offset are less than 3ppm.

Bandwidth: we use the same bandwidth as for AnalogCast, SoftCast and JPEG2000 systems. For JPEG2000 to fit into the same bandwidth as AnalogCast and SoftCast with modulation and FEC rates (bandwidth value depends on the system requirement, we only use the different modulation and FEC to make the same bandwidth as SoftCast), we use different compression ratio as in **TABLE I**:

TABLE I

FEC& Modulation	Source Rate(bpp)	PSNR without channel noise(dB)		
		Image1	Image2	Image3
1/2 FEC+BPSK	0.25	33.20	30.55	25.25
1/2 FEC+QPSK	0.5	36.30	32.70	28.27
3/4 FEC+QPSK	0.75	38.50	34.20	30.25
1/2 FEC+16QAM	1	40.03	35.46	32.14
3/4 FEC+16QAM	1.5	43.07	37.74	35.39
2/3 FEC+64QAM	2	45.02	39.83	38.12
3/4 FEC+64QAM	2.25	46.08	41.02	39.35

Metric: we compare the schemes using PSNR. It is a standard measure of video/image quality [8] and it is defined as a function of the mean squared error between all pixels as follow:

$$PSNR=10log_{10}\frac{(2^L-1)^2}{MSE}[dB] \tag{16}$$

4. EXPERIMENTAL RESULTS

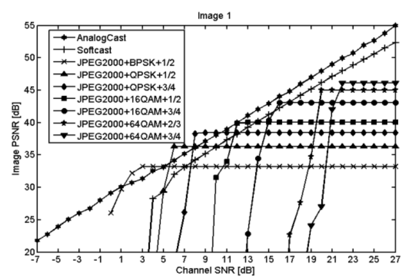
4.1. Benchmark Results: In this subsection we evaluate the performance of AnalogCast under broadcasting channels, compared with the other two schemes, SoftCast and JPEG2000. We perform the test by Matlab and no packet loss happened in this test. **Fig.5** shows the results of our test.

We can see that the JPEG2000 system has an obvious cliff effect. For SoftCast system, it also has a fall-off threshold because of side information's using digital coding. But when channel condition goes better the image quality will increase.

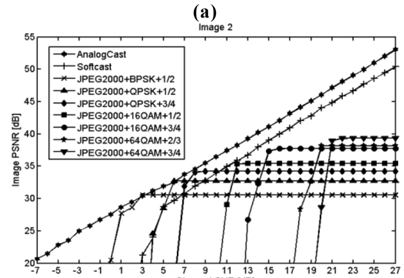
The AnalogCast performs comparably better than SoftCast by at least 1.5dB when both systems work well. It can also be seen that AnalogCast performs much better than all digital schemes, which can be considered as the unicast performance of JPEG2000.

Also the AnalogCast can work well when channel SNR is below 3dB. SoftCast and JPEG2000 image quality will drop on low SNR. So the AnalogCast mobility is better than other systems.

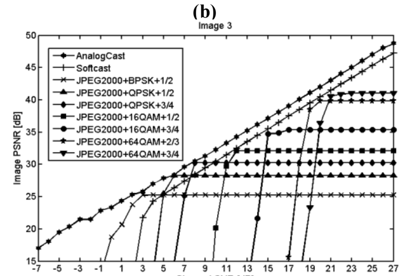
For the bandwidth, when channel SNR is higher than 20dB, the AnalogCast is better than 2.25bpp JPEG2000 compression. For a QPSK+3/4 FEC system which is the common configuration of satellite communications, to achieve the same performance, the JPEG2000 must use three times of the bandwidth of AnalogCast or SoftCast. Compared with AnalogCast and SoftCast, the AnalogCast doesn't need to send the side information. It will save about 2% [1] bandwidth at most. Avoiding side information transmission also reduce the computing resources caused by digital coding.



(a)



(b)



(c)

Fig5 Boradcasting performance. (a) Image 1. (b) Image 2. (c) Image 3.

4.2. Robustness to Packet Loss: As we discussed in **Section II** and **Section III**, we test the GOP interweave performance by two tests. In each test, we use 64 frames of image2 to do our examination and divide those frames into 8192 packets. We use burst packet loss and random packet loss in two tests, respectively. The channel noise of our tests is 8dB.

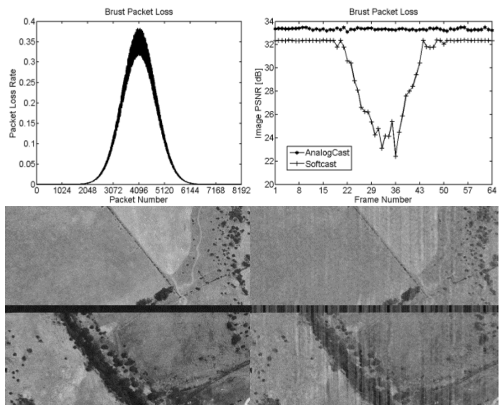


Fig6 Burst Packet Loss Test. The left top to the right bottom: (1) Packet Loss Rate. (2) System Performance. (3) Frame 32 of AnalogCast. (4) Frame 32 of SoftCast.

Fig.6 shows the results of burst packet loss test, we can see the SoftCast system's image PSNR is worse when packet loss rate is higher. In Frame 32 and Frame 33 the PSNR drops to 24.3dB. Compared with SoftCast, the AnalogCast performs smoothly and the image PSNR maintains around 33dB. It means our system has more robustness than SoftCast.

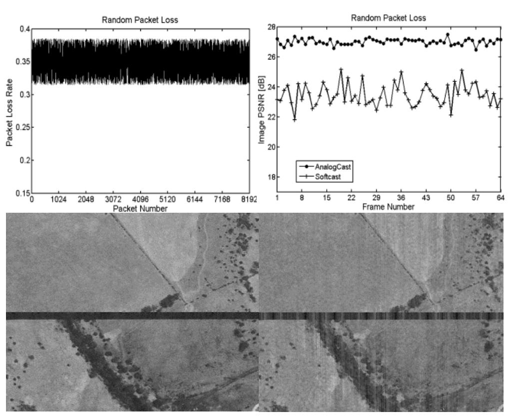
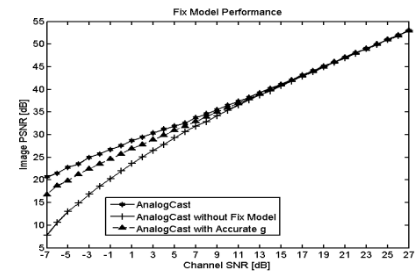


Fig7 Random Packet Loss Test. The left top to the right bottom: (1) Packet Loss Rate. (2) System Performance. (3) Frame 32 of AnalogCast. (4) Frame 32 of Softcast.

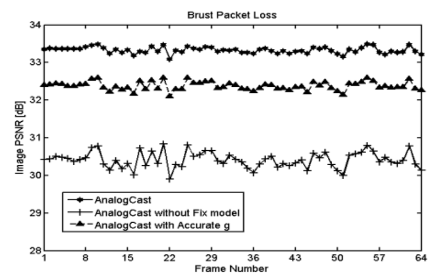
Fig.7 shows the results of random packet loss test, we can see the AnalogCast image quality is smoother and better than SoftCast. Interestingly, the AnalogCast image perceptual quality is noticeably better than SoftCast.

4.3. Scale Factor Fix Curve-Fitting Model Performance: We evaluate the performance of different parts of AnalogCast under broadcasting channels by three tests. In those tests, there are three schemes compared, AnalogCast, AnalogCast without scale factor fix curve-fitting model and AnalogCast with accurate g. In each test, we send 64 frames of image2 by 8192 packets to the receivers. In the first test, the measurements' SNRs span from -7 to 27 dB and no packet loss happens. In the second and third tests the packet loss is random and in bursts, the packet loss rate of each packet is shown in **Fig6** and **Fig7**. The channel noise of the two tests is 8dB.

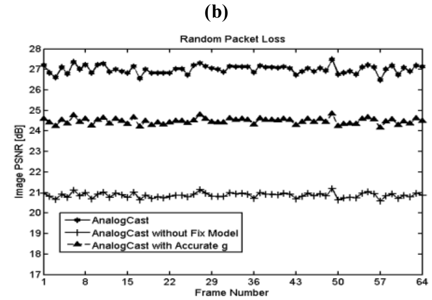
The **Fig8.(a)** shows that the model can improve the image quality by at least 4 dB for AnalogCast without fix model and 1 dB to AnalogCast with accurate g when channel condition is worse than 3 dB. At high SNRs the decoder quality is good enough and scale factor fix curve-fitting model produces a smaller effect. The **Fig8.(b)** and **Fig8.(c)** show that the model can improve image quality by 3dB~6dB under packet loss compared with AnalogCast without fix model and better performance than AnalogCast with accurate g about 1dB~3dB. This is because the model fixes the amplitude change of $u_{i,j}$ caused by Gaussian noise and the accurate g doesn't do this work.



(a)



(b)



(c)

Fig8. Scale Factor Fix Curve-Fitting Model Performance. (a) Channel noise performance test. (b) Random packet loss test with 8dB noise. (c) Burst packet loss test with 8dB noise.

5. CONCLUSIONS

This paper presents a novel wireless image transmission scheme named AnalogCast. Compared with the SoftCast, AnalogCast uses pseudo analog coding to avoid "cliff effect" to get the good scalability and uses the data whitening to improve system robustness. Further, AnalogCast uses scale factor estimate based on L-shaped chunk division and scale factor fix curve-fitting model to get better mobility, less bandwidth cost and computational budget than SoftCast. To protect the packet loss, we designed a mode of GOP interweave to smooth the image quality and improve perceptual quality. These results promise the higher resolution satellite image broadcasting service in the future.

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