A Short History of Packet Video 1987–2007: From an Esoteric Topic to a Core Technology
(A personal view…)

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joint work with M.Garrett (Telcordia), G.Karlsson (KTH), and S.McCanne (Riverbed),
M.Gastpar (UCBerkeley), P.Prandoni (QuiVidi), A.Cunha and M.Do (UIUC)
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Audiovisual Communications Laboratory
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
1. A bit of history
   The Center for Telecommunications Research, Columbia University
   The first Packet Video Workshop (May 1 1987)

2. The first incarnation of packet video
   When real-time video coding was hard…. Bit rate traces
   Joint source-channel coding and robust video coding
   Internet packet video and the Mbone

3. Remember, the dotcom bubble and … burst
   An example: FastForwardNetworks

4. On the interaction of source and channel coding
   To separate or not to separate...
   Gaussian sensor networks

5. Some current projects related to image and video
   The plenoptic function and models for video
   SensorScope and the autonomous camera project

6. Conclusions
   A happy ending (Riverbed ;)
Acknowledgements

• To the organizers, Pascal Frossard in particular!
• Swiss and US NSF, our good friends and sponsors
• Gunnar Karlsson, first grad. student, worked on video coding for packet networks
• Mark Garrett, a networking grad. student and researcher at Bellcore, source of the famous StarWars bitrate trace
• Steve McCanne, grad. student at UCBerkeley and researcher at LBL, author of many of the early tools for multimedia on the internet, and a serial entrepreneur
• Michael Gastpar, EPFL and now at UCBerkeley, for some fundamental work on joint source-channel coding
• Arthur Cunha and Minh Do at UIUC, for new traces, based on the plenoptic function
• Paolo Prandoni, EPFL and now QuiVidi, for the autonomous camera
• Special thanks to Bernd Girod, for providing very useful data (Fig.1) and enduring… the third talk ;)}
1. History

Columbia University’s Center for Telecommunications Research

- National center, ERC funded by NSF
- Created in 1985, just after the break up
- Ambitious goal (the “academic” center for the future of telecommunications)

Research topics

- High speed packet networks (MAGNET)
- Queuing theory
- Signal processing
- Interdisciplinary research… packet services!

In 1986:

- Packet voice invented by BBN in the 60’s
- Packet video a dream, hard to implement
1. History

The first workshop on Packet Video

– Sense that it was an emerging topic
– Put together in a rush....
– But quite interesting!

Research topics

– Video coding
– Queuing theory
– Switching
1. History

Experiments

Session A: Experiences and Applications of Packet Video
Channel Sharing by Interframe Video Codecs, B.Haskell ........................................ 3
Experiences with Packet Video over Satellite, S.Casner ........................................... 3
A Variable Bit Rate Video Codec, W.Verbist ............................................................... 4
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Concept of Multi-Point Teleconference in Each One’s Room by Packetized Video Technique, Y.Yasuda .......................................................... 5
Status of Packet Video Experiments on Bellcore METROCORE Network, M.Garrett ... 6
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Algorithms

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Variable Rate Video Transmission in Asynchronous Transfer Mode Networks, N.Ohta . 7
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Forward Error Correction Coding for Packet Loss Protection, P.J.Lee ....................... 9
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1. History

Architecture and performance
Outline

1. A bit of history

2. The first incarnation of packet video
   - When real-time video coding was hard….
   - Bit rate traces
   - Joint source-channel coding
   - Robust video coding
   - Internet packet video and the Mbone

3. Remember, the dotcom bubble and … burst

4. On the interaction of source and channel coding

5. Some current projects related to image and video

6. Conclusions
M. Garrett is interested in data for performance analysis of packet video systems. He compresses the entire StarWars movie, intra-frame, block DCT.

First trace of … self-similarity, long range dependence!
To separate, or not to separate, that is the question!
To separate, or not to separate, that is the question!

Interaction of source and channel coding

Full reconstruction

Coarse reconstruction

High priority, high protection

Low priority, little protection

MR coder
JSCC for error resilience and multicast

- There is no separation
- Finite block lengths, high variability
- Broadcast, multicast
Van Jacobson
- The man who stabilized the internet (TCP/IP)

Steve McCanne
- The man who put multimedia on the internet ;)
- VAT and VIC
- The Mbone (Multicast backbone)
- Multimedia, Interfaces, and Graphics Seminar (UC Berkeley Course CS 298-5)
- The seminar has been webcast world-wide on the Internet since it was first offered in the Spring 1995 semester.
**The MBone**

**Multicast overlay network**
- Part of experimental infrastructure on the internet, early 90’s

**Example:**
- On June 24, 1993, Severe Tire Damage was broadcast live from the patios of Xerox PARC onto the MBONE, both audio and video. The band was seen and heard live as far away as Australia.
- Nov 18 1994: Rolling Stones concert multicast on internet
  
  “I want to say a special welcome to everyone that’s climbed into the internet tonight, and has got into the Mbone…and I hope it doesn’y all collapse!”
  
  Mick Jagger, 11/18/94

![Figure 1.1: MBone Timeline.](image-url)
UC Berkeley CS 298-5 Seminar, Spring 1995, on MBone

1/20/95: Introduction (Rowe, Vetterli, Sequin, UCB)
1/27/95: "U.C. Berkeley Digital Library Project" (Wilensky, UCB)
2/3/95: "Multimedia Network Protocols: Where are We?" (Ferrari, UCB)
2/10/95: "Motion in Video Compression: What's it good for?" (Orchard, U Illinois)
2/17/95: "The MBone - Interactive Multimedia on the Internet" (Van Jacobson, LBL)
2/24/95: "Making Sense with Multimedia" (Russell, Apple)
3/3/95: "IPng: The Next Generation Internet Protocol" (Deering, Xerox PARC)
3/10/95: "ATM Flow Control" (Lauer, MERL)
3/17/95: "No Title Supplied" (Tognazzini, Sun)
3/24/95: "Human Vision Models for Image Compression (Klein, UCB)
4/7/95: "Distributed Objects for Interactive TV" (Mark Linton, SGI)
4/14/95: "QuickTime Conferencing “(Eric Hoffert, Apple)
4/21/95: SEMINAR CANCELED (Richard Baker, PictureTel)
4/28/95: "Two Techniques for Enabling Ubiquitous True-VOD" (Little)
5/5/95: "Signal Adaptive Subband Audio Compression" (Princen, SGI)
The Mbone: Example of tools (1995)
Joint source-channel coding (subband coding ;)
Receiver driven multicast
• Different layers over different trees
• Automatic subscribe/unsubscribe
• Dynamic quality management
Steve McCanne’s dissertation

- Got him an assistant prof. position straight out of PhD…. At UC Berkeley
- Several highly cited papers
- ACM Best Dissertation Award
- From the Berkeleyan, March 1998: Steven McCanne, assistant professor of EECS, has received the ACM Dissertation Award from the Association for Computing Machinery. McCanne earned his doctorate from Berkeley in 1996, the same year he joined the faculty. His award-winning dissertation is on “Scalable Compression and Transmission of Internet Multicast Video.” He specializes in multimedia networking and multicast communications.
## 1. History: Courtesy of Bernd Girod with thanks

![Timeline of Internet media delivery](image)

### Figure 1. Brief history of Internet media delivery.

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>'92</td>
<td>MBone audiocast of IETF mtg</td>
</tr>
<tr>
<td>'93</td>
<td>MBone audiocast Rolling Stones</td>
</tr>
<tr>
<td>'94</td>
<td>ITU-T Rec. H.263</td>
</tr>
<tr>
<td>'95</td>
<td>Intel Pentium</td>
</tr>
<tr>
<td>'96</td>
<td>TiVo PVR</td>
</tr>
<tr>
<td>'97</td>
<td>Akamai edge servers</td>
</tr>
<tr>
<td>'98</td>
<td>MPEG-4</td>
</tr>
<tr>
<td>'99</td>
<td>Napster, P2P file sharing</td>
</tr>
<tr>
<td>'00</td>
<td>Napster shut down</td>
</tr>
<tr>
<td>'01</td>
<td>Kazaa</td>
</tr>
<tr>
<td>'02</td>
<td>BitTorrent</td>
</tr>
<tr>
<td>'03</td>
<td>H.264/AVC</td>
</tr>
<tr>
<td>'04</td>
<td>Microsoft VC-1</td>
</tr>
<tr>
<td>'05</td>
<td>SMPTE standard</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
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</tr>
</thead>
<tbody>
<tr>
<td>'99</td>
<td>RealAudio 1.0</td>
</tr>
<tr>
<td>'00</td>
<td>Netscape 1.0</td>
</tr>
<tr>
<td>'01</td>
<td>VivoActive</td>
</tr>
<tr>
<td>'02</td>
<td>RealVideo 1.0</td>
</tr>
<tr>
<td>'03</td>
<td>Microsoft NetShow streaming</td>
</tr>
<tr>
<td>'04</td>
<td>Netscape becomes Windows media</td>
</tr>
<tr>
<td>'05</td>
<td>RealPlayer reaches 10M users</td>
</tr>
<tr>
<td>'94</td>
<td>Apple Quicktime streaming</td>
</tr>
<tr>
<td>'97</td>
<td>Apple iPod</td>
</tr>
<tr>
<td>'98</td>
<td>Wireless video streaming</td>
</tr>
<tr>
<td>'99</td>
<td>Verizon V-Cast, MobiTV</td>
</tr>
<tr>
<td>'00</td>
<td>Podcasting</td>
</tr>
</tbody>
</table>
Outline

1. A bit of history

2. The first incarnation of packet video

3. Remember, the dotcom bubble and ... burst
   An example: FastForwardNetworks
   Fast growth and ...

4. On the interaction of source and channel coding

5. Some current projects related to image and video

6. Conclusions
Steve McCanne’s first company

Co-founded FastForward Networks in 1998
Business model: Build it, they will come!
  - Generalized client-server model
  - Broadcast POP
  - Potential customers: Broadcast.com ;)

Figure 1: Generalizing the client/server model
Steve McCanne’s first company

• After 2.5 years of rapid growth…

Please note the details….Inktomi (another Berkeley startup, at 108.75)
Outline

1. A bit of history
2. The first incarnation of packet video
3. Remember, the dotcom bubble and … burst
4. On the interaction of source and channel coding
   To separate or not to separate...
   A simple example
   Gaussian sensor networks
5. Some current projects related to image and video
6. Conclusions
4. On the interaction of source and channel coding

Going digital is tightly linked to the separation principle:

- in the point to point case, separation allows to use “bits” as a universal currency

- but this is a miracle! (or a lucky coincidence)

**There is no reason that in multipoint source-channel transmission the “bit” currency will hold (M.Gastpar)**

**Multi-source, multi-sink case:**

- correlated source coding
- uncoded transmission can be optimal
- source-channel coding for sensor networks
A famous and cautionary example

In point to point, if $R < C$, all is well in Shannon land. In multipoint communication, things are trickier (or more interesting)

Famous textbook counter example (e.g. Cover-Thomas)

No intersection, but communication possible!
[GastparV:03/04]
Consider the problem of sensing
- one source of analog information but many sensors
- reconstruct an estimate at the base station

Model: The CEO problem [Berger et al], Gaussian case

**Question:** distributed source compression and MIMO transmission or uncoded transmission?
Example: Gaussian Source, Gaussian Noise

Performance (cst or poly. growing power shared among sensors):
- with uncoded transmission: \( \text{MSE} = O\left(\frac{1}{M}\right) \)
- with separation: \( \text{MSE} = O\left(\frac{1}{\log M}\right) \)
- Exponential suboptimality!

Communication between sensors does not help as M grows!

Intriguing remark:
- by going to “bits”, MSE went from 1/M to 1/Log(M)
- “bits” might not be a good for distributed sensing and communications

If not “bits”, what is information in networks? [Gastpar:02]
Remarks on the separation principle

Many cases are open
- Sensor network: no separation…
- Broadcast: no separation…
- Gathering: no separation…
- Relaying: no separation…

See M. Gastpar’s thesis for an excellent review

Practice: separation is a key architectural feature

Digital is almost not escapable!
Outline

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2. The first incarnation of packet video
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4. On the interaction of source and channel coding
5. Some current projects related to image and video
   The plenoptic function
   Models for video
   SensorScope
   The autonomous camera project
6. Conclusions
The Plenoptic Function [Adelson]

Multiple camera systems
- physical world (e.g. landscape, room)
- distributed signal acquisition
- possible images: plenoptic function, 7-dim!

Background:
- pinhole camera
- epipolar geometry
- multidimensional sampling

Implications on communications
- camera sources are correlated in a particular way
- limits on number on “independent” cameras
- different BW requirements at different locations
The POF as a generator of video

Many practical scenarios can be represented in this setting

Two sources of complexity:

- the camera trajectory
- the “reality” around it

Suggests a model of $\text{POF}(W(t), t)$. 
Question: *what are the information rates of the source?*

Two coding problems:

- *reconstruct the reality,*
- *reconstruct sequence of sample realities (e.g. video)*
A Simplified Model: Bernoulli Camera + iid Painted Wall

- An ensemble of trajectories modeled with a random walk.
- An ensemble of realities that are modeled with a strip/wall of stationary pixels drawn from an alphabet.
- The pixels are assumed to be independent of trajectory.
- Simplest example: $X_n$ iid, and $N_i \sim Bern(p_W)$. 
• Model leads to a vector process $V$ over time indexed by $t$:

$$V_t := (X_{W_t}; X_{W_t+1}; \cdots; X_{W_t+L})$$

• Can show process is *stationary and mean-ergodic* if $X$ is *stationary and mean-ergodic*.

• We are thus ready to ask information-theoretic questions about the process $V$. 
Memory and Recurrence

Amount of bits saved with memory depends on rate of recurrence...

- When $p_W = 0.5$, we have a recurrent trajectory --- results in lower bitrate

- By contrast, $p_W = 0$ means camera panning --- scene changes increase bitrate

- Eg: Hollywood sitcom -- *highly recurrent* (same background over and over again).

Can be used for analysis of statistical multiplexing gain…
5.2 The SensorScope Project [MICS]

(G. Barrenetxea, H. Dubois-Ferriere, T. Schmid)

http://sensorscope.epfl.ch

What are we trying to accomplish?

SensorScope:
- distributed sensing instrument
- relevant datasets with clear documentation
- all data on-line, real-time
- anybody can compute/analyze with

Sensor nodes:
- many possible platforms inc. low power (Berkeley motes, tinynode, tmote)
- many types of sensing (e.g. cyclops)

Deployments
- a few dozen nodes to 110 nodes
- self-organized network up for 9 months
- large dataset collects

Locations: EPFL Campus wide, Plaine Morte, Eawag, EPFL RoofNet, HES-SO FishNet, Le Genepi, Grand-St-Bernard
The core of SensorScope: WeatherStation

**WeatherStation**
- centered around Tinynode (lowest-power sensor node)
- solar energy subsystem: energy autonomous
- water proof housing
- seven external sensors measuring:
  - temperature (ambient and surface)
  - humidity
  - wind speed and direction
  - soil moisture
  - solar radiation
  - precipitation

Solar energy system                             First Prototype                             WeatherStation
WeatherStation Deployment and Web Interface

Objective:

- Relevant datasets with clear documentation
- All data on-line: http://sensorscope.epfl.ch/
- Anybody can compute/analyze with
The Autonomous Camera Project (P. Prandoni)

• **Challenges:**
  – harsh environmental conditions
  – low data rate for communication
  – severe energy limitation

• **Wish list:**
  – open system, cross-platform software
  – flexible and reusable architecture
  – quick prototyping:
    1.5 month from green light to deployment

• **Solution:**
  – off-the-shelf integrated hardware: Trolltech’s Greenphone
  – outsourcing
Software:

- Genepi or Mars, it’s (almost) the same; we need autonomous recovery:
  - GPRS crashes, FTP timeouts
  - Power outages
  - Bugs in the OS, clock drifts, etc
  - Must allow for remote code patching
Interface:

- Deployment:
- Remote access:
  - patch files
  - phone calls trigger a snapshot
  - SMS; example of an emergency bug fix:

```bash
system killall g_qsensor-watchdog.sh; ash -c "ls; killall qsensor; sleep 9 ;cp /mnt/disk2/home/4.2/Documents/epfl/patches/qsensor /mnt/disk2/epfl/apps/ ; reboot"
```
Hardware:

- Power supply:
  - car battery + solar panel
  - external reset circuitry
  - waterproof box
- Remarkably robust (it’s cold up there):

![Graph showing sensor data over time](image-url)
Deployment:

Le Genepi:
Rock Glacier Génépi Experiment September-October 2007
3D air temperature spatial distribution
Can double up as surveillance….  

From: Paolo Prandoni paolo.prandoni@gmail.com  
Date: November 7, 2007 9:53:54 AM GMT+01:00  
To: Guillermo Barrenetxea <guillermo.barrenetxea@epfl.ch>  
Subject: Security camera!  
SOMEONE'S STEALING THE SENSORS!!!!
6. Conclusions

Packet video
- From a curiosity to an expected service
- Many new tricks in the box
- Network coding
- In-network processing
- Multiple description coding
- Distributed compression

The wired case
- Peer-to-peer distribution networks
- Fountains
- Sophisticated codes

The wireless case
- Probably where the action is
- More constrained, more interesting?
- Peer-to-peer not there yet

From joint source-channel coding to source-channel communication
- This goes back to Shannon’s original question, but multi-source multi-point communication is hard...
A Happy Ending!

• Steve McCanne’s second company: Co-founded Riverbed

• WLAN Acceleration

• From the news:
• Riverbed strikes it rich in first day of trading
  22 Sep 2006 | SearchStorage.com
Riverbed releases first shares
Riverbed Technology Inc. announced an initial public offering of 8.7 million shares of its common stock at a price of $9.75 per share, a higher price than the predicted $7. Riverbed's common stock, listed on the NASDAQ Global Market under the symbol "RVBD," closed at $15.30 Thursday, for a total increase of $5.55, or 57% from the opening price. Riverbed is the first storage company to go public in more than two years.
Thank you for your attention!

Questions?

http://panorama.epfl.ch
• **Early work on video multicast**

• **On video bitrate analysis**
  – A. Cunha, M. Do, M. Vetterli, On the information rate of the plenoptic function, to be submitted

• **On sensor networks and separation**