HDTV: The Engineering History

`

12/10/99

Salvador Alvarez
James Chen
David Lecumberri
Chen-Pang Yang

Index

Introduction

“The world is moving towards High Definition Television [HDTV]” “Don’t buy a regular TV now, they are going to be better in every way when HDTV comes into market”. Some of the many phrases dropped by people who are loosely following the HDTV effort. When asked, “How do you know?”, these people confidently responded with, “Because technology is just going to get better and better.” Though HDTV is revolutionizing the world, and the technology is getting better, very little thought is put into the effort done by engineers in the leading companies. People expect television to constantly improve, but these improvements do not occur on their own. Rather, they arise from many different factors, such as nationalistic politicians who push American companies to develop HDTV, the computer industry pushing for a digital television, or engineers inventing new ideas.

In Inventing Accuracy, Donald Mackenzie clearly describes a false perception people have regarding improvements in technology, a notion he refers to as a natural trajectory. Through a chronology of the history of nuclear missile guidance, he defines such a trajectory as "a direction of technical development that is simply natural, not created by social interests but corresponding to the inherent possibilities of the technology (pg 167). However, in the context of military guidance, he comes to the conclusion that these things can't really exist. All trajectories need to be helped along by technical, social, and political pressures. Nothing happens by itself.

Even so, people still believe technologies advance because it is natural phenomenon. Moore’s Law is a prediction that the pace of microchip technology change is such that the amount of data storage that a microchip can hold doubles every year or at least every 18 months. Intel’s 8080 in 1975 had 4500 transistors. In 1995, when Intel introduced the Pentium Pro, it had 5.5 million transistors. However it did not occur because it was on a predestined plan to do so, but rather engineers in Santa Clara working hard to compete with other companies. If no other company that creating chips existed, Intel would most likely be just as happy to fire all its engineers and sell their chips at high prices.

HDTV is no different. This paper strives to analyze HDTV as the product of technological trajectories similar to the way Mackenzie did for nuclear missile guidance. To look under the mask of the natural trajectory and present HDTV as a true product of its surroundings, a manifestation of corporate interests, technical desires, and government goals. This paper also will show that HDTV is not really the natural way of the world, but one method that has been contrived through the involvement of lots of different parties, and done so successfully enough to convince the nation that it's a natural thing that should be expected and accepted by society as a great technological advancement.

1. Pre-HDTV History

In 1985, Motorola, major manufacturer of two-way radios, led a lobbying effort to reclaim unused television airwaves to expand the allocated spectrum used by two-way radios. This lobbying effort became known as Land Mobile. The National Association of Broadcasters (NAB) was not going to let the FCC reallocate the airwaves without a fight. After all, those airwaves belonged to the broadcasters, and they felt their existence depended on them. But by 1986, the FCC appeared willing to turn over the airwaves [26, p. 8].

John Abel, president of NAB, led the effort to fend off the momentum of Land Mobile by trying to convince the FCC that broadcasters needed their airwaves. However, as far as Motorola and the FCC saw the issue, the bottom line was that broadcasters were not using the airwaves and therefore there was no reason to allow them to keep the airwaves. After much thought, Abel thought of the idea of pitching HDTV to the FCC. The broadcasters knew the current, and only, HDTV system was in Japan, and their system required more than one channel. Though some broadcasters were against the idea, because of the large investment required to redo their infrastructure if HDTV was forced upon them, they also knew the Land Mobile issue was a more immediate problem.

The NAB invited NHK, Japan's public broadcasting company, to do a demonstration in Washington. The NAB hoped to convince the FCC commissioner that America needed HDTV, and if their airwaves were taken from them, then America would never receive HDTV. NHK meanwhile had no idea of the true intention of NAB and was scheduled to demonstrate their HDTV system on January 7, 1987.

In 1986, NHK had tried to set the world's technical standards at the Consultive Committee of International Radio. By setting the standards, Japanese television makers could easily sell their televisions in foreign countries. The US State Department in 1986 liked the idea. If everybody had the same system, the movie industry could easily distribute their films around the world. [29, p. 47] Additionally, the standards would have little effect in the United States, since American television manufacturers had become nearly non-existent after years of losing the market to Japanese manufacturers. However, the Europeans strongly opposed Japanese products flooding their markets while Americans easily pushed their cultural imperialism onto their citizens. Thus, NHK's plans of setting the world's standard were crushed. But now NHK was to do a demo in Washington, and with the demonstration, an opportunity to convince the Americans to adopt NHK's technical standard.

The NHK demonstration at the FCC did not go well for Abel. The FCC chairman, Mark Fowler, saw right though Abel's intentions and left the demonstration before NHK showcased their HDTV system. Abel felt that the demonstration was pointless now. Still, for those who were there and saw the demonstration, they were wowed to say the least. NHK was to do one more demonstration at the capitol. The response of the senators and congressmen was shock to see a Japanese firm with technology much more advanced than the United States had to offer. Then-Senator Al Gore at the time pointed out two main issues. First was whether the United States would be a factor in the global market for HDTV and HDTV-related technologies. Secondly, there was a concern in the future of the US semiconductor industry and the implications for that industry of and HDTV market dominated by foreign enterprises. Thirdly, a loss of dominance in the computer industry if HDTV and computers became intertwined with each other. [28, p. 138] Representative Don Ritter felt that "to miss out on HDTV is to miss out on the 21st century." [29, p. 39] With theses concerns at hand, a sense of American nationalism and protectionism toward the television industry was now set.

FCC began facing political pressure for an American HDTV system. Within a month of the demonstration at the capitol, Fowler testified to a Senate subcommittee. They were concerned Land Mobile would delay an American HDTV system, if one were ever to develop. Fowler then put Land Mobile on hold. The broadcasters still had work to do if they were to keep their airwaves. Fowler decided to return to the private sector and resigned. Dennis Patrick succeeded Fowler as the new FCC chairman. John Blake, a Washington lawyer, convinced Patrick that HDTV was needed. Blake's arguments were that the broadcast industry could not survive if it was not allowed to broadcast in HDTV, and with the broadcasters, America's tradition of free, local broadcasting would not survive [26].

The FCC reversed its decision on Land Mobile. The broadcasters had won, and in April of '87, this decision was formally announced. In August, a special three-month inquiry into HDTV in the United States began. At the end of the inquiry, Patrick had political pressure to do something. He therefore created an advisory committee to study the issue. This kept Washington off his back, and the broadcasters were also pleased, as they knew how slow committees worked. After all, the broadcasters weren't in a hurry to rebuild their infrastructure. The Advisory Committee on Advanced Television Service (ACATS) was formed with Dick Wiley appointed chairman. As Wiley stated, the ACATS objective was "to look into the political, economical, and spectrum trade-offs involved in establishing a new transmission standard." [28, p. 12]

2. HDTV in the US: A race started by the government.

The first challenge ACATS faced was defining the requirements for what could be considered "advanced television". Initially the FCC decided that a revolutionary system that made all current television sets obsolete was not in the best interest of the American public. Therefore, at the core of the FCC guidelines were:

- **An NTSC Compatible system**: the FCC ruled that the new system should be compatible with the existing NTSC systems. This meant that NTSC receivers should be able to pick up the HDTV signal and display a reduced quality version, while the HDTV receiver would display the full image. This decision was quite conservative, since it would ensure that the whole TV manufacturing industry would not be shaken up. On the other hand, it would mean to carry forward all the limitations of the current system, thus seriously handicapping the possibilities of a clean new system (and there were a number of voices supporting this point).

- **Analog system**: although some efforts in developing digital HDTV systems had been made by then, it was a common belief that a true all-digital system was theoretically possible, but at the moment, not feasible. Though the desired technology was clearly digital, the goal was set on analog technology which would hopefully evolve into a digital system in the future (some predictions were talking around year 2005).

After ACATS declared their specifications for advanced television, they began receiving proposals. The proposals greatly varied. Some proposals were serious, viable, and from large corporations, while others were proposals from individuals of a system they threw together in their backyard. In November 1988, during a week that came to be known as "Hell Week", ACATS evaluated the proposals weeding out the systems they felt were not feasible. The initial 23 proposals were now reduced to 6.

November 1988 not only reduced the number of proposals to 6, but also elected George Bush to the White House as president. After the election, interest in HDTV was renewed in the political arena. Different government agencies, such as DARPA and House committees, began promising money, since they believed Bush would be more liberal in spending money than his predecessor. DARPA promised $30 million in grants and different Senate members proposed bills to provide up to $500 million! [26, p.38]. However, Bush administration declared the industry would have to carry on the HDTV effort without government money.

At the same time, ACATS was realizing that some means of testing was required to test the surviving proposals to determine the best system. Therefore ACATS formed the Advanced Television Test Center in Alexandria, VA, a consortium formed primarily be the broadcast industry. The qualification period of the ACATS race was coming to a close, as June 1990 was the deadline for proposals. As testing was scheduled to start in the following year, a substantial testing fee of $200,000 was imposed on the contestants, and a feeling of importance ensued through not only the contestants, but the regulators as well.

However, just months before the deadline entry, the FCC shifted its preference to a “true” HDTV system in March 1990. This meant that the FCC turned away from and NTSC compatible approach and now favored a simulcast system, one in which HDTV and NTSC programming would be transmitted simultaneously on different channels during the transition from NTSC to HDTV. The decision was influenced by a breakthrough in technology that occurred in early 1990 when General Instruments (GI) announced they developed an all-digital system, changing the coarse of the race.

2.1. The Industry Reaction

In the late 1980’s, the US TV industry was composed of several different groups with varying interests and goals. On one side were the broadcasters who pursued HDTV as a means of keeping the unused channels Land Mobile threatened to take away. One the other side is the manufactures, which were in poor shape, consistently losing their market share to Japan. The once proud American television industry was reduced to RCA and Zenith. Though their interest in achieving an HDTV system stemmed from different reasons, these manufactures would be part of the core of competing HDTV proposals.

In December 1985, General Electric purchased RCA, the once proud inventor of color television. Slightly more than a year later, February 1987, the research division of RCA, Sarnoff Research Center, was segregated and donated to SRI International. Sarnoff was now under increased pressure to produce results, however, with an equal amount of strong traditional of innovation, Sarnoff was highly motivated to be the leader in HDTV.

General Electric sold the remainder of RCA to Thomson, a French company, later that year. Thomson hired Sarnoff as its research facility in North America while Philips, another European company, entered the US HDTV race by joining the Thomson-Sarnoff partnership in 1989.

Sarnoff began working on an Advanced Compatible TV system (ACTV), an analog NTSC-compatible system that was their primary entry to the HDTV race. However, during their system development, the FCC switched to simulcast, discarding the requirement for backward compatibility. Furthermore, companies began developing digital HDTV systems, making the Sarnoff system outdated. Therefore, after 1990, Sarnoff needed to readdress their efforts to produce a digital entry for the competition.

However, Zenith became involved with the HDTV race for completely different reasons. For several years, Zenith had experienced serious financial difficulties and decided to analyze the HDTV competition for potential benefits. They hoped their participation in the HDTV revolution would help them ameliorate their financial matters. In fact, Wayne Luplow, the VP of R&D at Zenith, refers to Zenith's dependence on this project as "The Great White Hope" since Zenith hoped the project would pull them out of their dismal fiscal situation.[26, p. 79] However, the Zenith corporate culture dictated a meeker environment. That is to say, Zenith was truly more of a follower than an innovator, according to Professor Jae Lim.[4] Zenith's president, Jerry Pearlman, soon realized the company could not design a suitable HDTV entry itself, and began to seek partnership with a stronger company. In mid-1989, AT&T Bell Labs joined Zenith in its mission to develop a partially digital HDTV entry, which included a motion estimator to be developed by Bell Labs.

General Instruments, a company unknown to the TV industry, was a surprise entry into the ACATS race. However, General Instruments had a strong background in digital communcations. A year before the ACATS was formed, GI purchased a California-based company called VideoCipher Division. VideoCipher had become known for the manufacture of a digital scrambling system for HBO, called VideoCipher II, and also had significant experience in encrypted digital satellite communications. They became interested in the race when, after toying with the idea of entering the HDTV contest, their engineers produced a design for an all-digital system. Although the system was only a simulation (no hardware had actually been built), it introduced a major breakthrough in the early 1990's when the television industry still saw fully digital TV as an unfulfilled, futuristic goal. When GI began demonstrating their system, the potential of HDTV increased to include connectivity with computing technologies and other communication developments. [6] In fact, these demonstrations actually reinforced the ACATS determination to select a system that would offer the full scope of digital television possibilities.

MIT's involvement in the race begins with Bill Schreiber's communications research, funded by the Center for Advanced Television Studies, a consortium formed by broadcasters and manufacturers around the nation. Since the beginning of the HDTV debates, Schreiber strongly advocated simulcast systems, and in fact submitted a proposal that managed to survive Hell Week. However, in 1989, after the renewal of funding for the HDTV effort, hosted then at Media Lab, was revoked, the CATS sponsors announced that they would invite other universities to research HDTV. Soon after, Bill Schreiber announced his intention of retiring. Many claim that he resigned because of the lack of funding for MIT's HDTV initiative.[3] Prof. Jae Lim, from the Research Laboratory of Electronics (RLE), took over Schreiber's effort and became the facilitator of MIT's involvement in HDTV.

By the end of 1990, there were five remaining proposals competing for the ACATS recommendation: Sarnoff-Thomson-Philips, Zenith-AT&T, GI, MIT, and NHK. ACATS decided the order of testing, as a function of how advanced were the systems. MIT, however, lacked the necessary economic resources to participate in the testing phase, due to the overwhelming testing fees, and was therefore given the final test slot. Tests would commence in September 1991 and would span 8 weeks time for each system, in the following order: Sarnoff's ACTV system, NHK, GI, Zenith-AT&T, Sarnoff-Thomson-Philips and, lastly, MIT.

In addition for MIT's need for financial support for testing fees, its system was far from being complete. GI, on the other hand, had presented the first digital system, but only as a simulated prototype, and there were concerns that their hardware implementation of the system would not be completed on schedule. MIT's position as the final entry was very valuable, since it meant almost an extra year of development. As a result, in December 1990, both corporations developed an alliance, forming the GI-MIT system. This agreement would allow MIT to participate and would give GI a virtual re-test one year later, since the significant portion of the joint entry would be drawn from GI's original entry. The other participants protested, arguing that GI's strategy was to get a second test with a year to improve upon their first entry. However, there was a major technical difference because the joint GI-MIT proposal would use progressive scanning, instead of interlaced scanning, as presented in the original GI entry. While his technical difference quieted the protests of the other participants, it proved to be only the first incident in the testing process, of which there were more to come.

This process clearly illustrates that each player had different reasons for participating in the race. The government, for example, was trying to revitalize a failing American television manufacturing industry. Each of the participating companies also had differing motivations, though many shared the common incentive of financial gain. In order to fully understand the HDTV debates, it is necessary to keep these different motivations in mind.

2.2. Organization of tests

The Advanced Television Test Center was ready to accommodate the systems for testing by September of 1991. Extensive tests for each system were supposed to run continuously for 8 weeks. To ensure the integrity of the system, it was agreed that once a system commenced testing, the engineers would be restricted from the equipment room, such that no mid-test modifications could be made. This rule, however, came to be one of the most disputed rules of testing.

The six systems under consideration began testing with the following characteristics:

- **Thompson-Sarnoff-Philip's ACTV**: Their original entry was a backwards-compatible, analog system. While the system had almost no chance of winning the HDTV contest, it was a good test of the test center itself.
- **NHK Narrow-Muse**: This was the Japanese system that was demonstrated in January 1997, modified to adapt to the terrestrial broadcasting required in the US (In Japan it was used over satellite). It was an analog system as well. Thus, with the promise of digital communication, it was becoming an antiquated technology. However, it was by far the most fully developed, implemented, and tested system at the time.

- **GI**: The tests for the GI system ran in late 1991. The system consisted of the original digital entry, which featured interlaced scanning, completed with a digital transmission system
- **Zenith-AT&T**: The testing ran in spring of 1992. It was an improvement over their original mixed analog/digital system, which became entirely digital-based system
- **Thompson-Sarnoff-Philip's HDTV**: Since their ACTV was virtually out of the race, they also presented a digital entry. The testing was performed in mid-1992.
- **MIT-GI**: By fall of 1992, more than a year after the GI system was tested, the joint MIT-GI system was presented before the ATTC. It was based on the original GI design, but featured progressive scanning.

Several instances that compromised the integrity of the testing process occurred. Because testing rules would not allow error correction during the course of the examination, companies began to argue for the correction of implementation errors, rather than design flaws. They argued that implementation errors should be allowed to be fixed, because such errors did not reflect poorly on the design, the focus of the tests. The problem came when engineers abused the term 'implementation errors' in cases where it was unclear whether or not corrections should be permitted.

Another example of the competitive atmosphere appears in the company's attitude towards each other. For instance, Professor Jae Lim required a progressive camera in order to demonstrate his progressive system. Zenith and AT&T possessed the few cameras that existed in the US and agreed to lend one to their fellow competitor for the modest price of $750,000! While Jae Lim was able to obtain a progressive tape recording from the ATTC archives, this incident is a prime example of how competitors treated each other [26, p.197].

2.3. HDTV: The test outcome

By February 1993, the testing period was concluding its final examinations. As a result, the ACATS scheduled an important meeting called the *Special Panel*. During this meeting, the final decision about the winning system was to be announced. However, much to the surprise of all the participants, the Special Panel concluded:

- Digital technology proved much better than analog. This conclusion allowed NHK to withdraw its proposal with dignity before it was ruled out of the competition
- There was not a clear winner among 4 digital systems. All of them were promising systems, but far from being complete.
- The ACATS recommended that since all systems were being gradually improved, a new set of tests would be performed some months later in order to reach a final decision.

Of course, after all the time, effort and money that the proponents had put into the competition, this was not the conclusion they wanted to hear. In fact, this result sparked the idea of having all companies join forces in a joint proposal, a consideration that pleased Dick Wiley, the ACATS chairman. The idea of another lengthy and costly testing process was not very appealing, especially when there could again be no decision at the end of the second round of testing. Even worse, there remained the possibility that three of the four systems could end up being discarded after almost five years of development. However, even though almost everyone thought an alliance would be the perfect solution, the strained relationships among the consortiums were far from allowing such a collaboration.

The new tests were scheduled to start on May 24, 1993, putting huge pressure on the competing consortiums, who wanted the alliance formed before the re-tests would begin. Momentum built up and on the very same day the new tests were scheduled to begin, the "Grand Alliance" was formed, a coalition that would combine the best of each of the four systems.

3. Organization of the Grand Alliance

At May 24, 1993, GI, Zenith, AT&T, MIT, Sarnoff, Philips, and Thomson formed the HDTV Grand Alliance.

Similar to the previous three strategic alliances in the competing phase, the Grand Alliance was more than a standard-making commercial consortium. Indeed, the eventual goal of this organization was to propose a universal HDTV standard for the United States. But the immediate task was to build an actual machine. It was on the basis of the specifications of this actual machine that the HDTV standard was established. In order to accomplish this task, the Grand Alliance was established as a ``virtual company" [1].

Figure 1 illustrates the organization of the Grand Alliance. The core entity of the Grand Alliance was the Technical Oversight Group (TOG). The TOG was constituted by eight chief engineers from the seven individual companies: Bob Rast (GI), Woo Paik (GI), Jae Lim (MIT), Don Leonard (Thomson), Glen Reitmeier (Sarnoff), Carlo Basile (Philips), Bill Beyers (AT&T), and Wayne Luplow (Zenith). The group was responsible for almost all the technical decisions for the GA HDTV system. Under the supervision of TOG, there were seven Specialist Groups: format, compression, transport, transmission, audio, systems, and interoperability. These subgroups were responsible for working out all the technical details in the aspects of their respective expertise. In order to avoid single participant's dominance over a specific technology in the decision process, each subgroup was open to all the seven companies. Theoretically, each company should have its members in all the subgroups.

The principal task of this organization was to design the specification of the GA HDTV system, and supervised the build-up process of the actual machine. When a technical choice must be made, the members of the relevant Specialist Groups worked out suggestions and submitted them to the TOG. If a consensus within the TOG was difficult to form, then the TOG had to vote. Any voting decision was passed by simple majority. Depending on occasions, there could be four votes or seven votes in sum [Smith]. The four-vote system basically grouped the seven participants with their old allies: Sarnoff/Thomson/Philips had one, AT&T/Zenith had one, GI had one, and MIT had one. In the seven-vote case, on the other hand, each individual company had a vote. To our knowledge, the two most important technical decisions made in the Grand Alliance—the adoption of Dolby AC-3 audio system, and the choice of Zenith VSB transmission technology-- were both made in a four-vote basis.

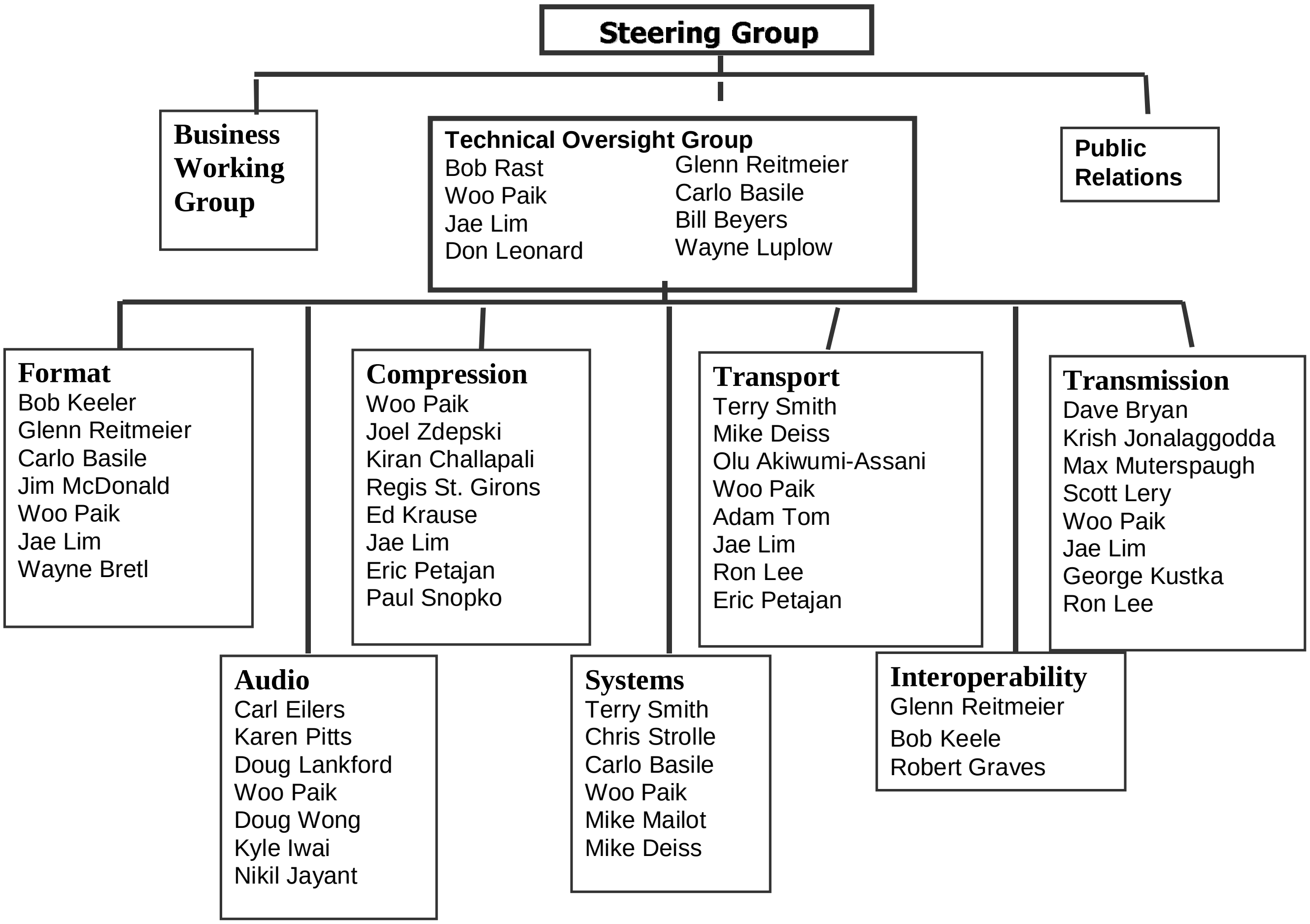

Figure 1. The Grand Alliance organization (courtesy to Dr. Glenn Reitmeier, Sarnoff corporation).

The members of the TOG and the Specialist Groups interacted and communicated intensively with one another. Conceivably the work of standard-making involved a lot of discussion, negotiation, and argument. In the case of the Grand Alliance, a significant amount of them was done verbally. The TOG members had a teleconference every Monday afternoon, and met in person monthly [1][4]. A typical teleconference last three to four hours. Jay Lim recalled that about half of his time on this project was spent on conference calls and meetings [4]. Neither was there less verbal communication on the Specialist Groups.

The decision-making style of the Grand Alliance was not dogmatic. There was no hegemonic figure, such as Charles Stark Draper or Tom West, on the engineering level of this project. Decision was not imposed from the top. Instead, the process was formally ``democratic''. Every company had an equal vote in the TOG. Moreover, from the viewpoint of the engineers,

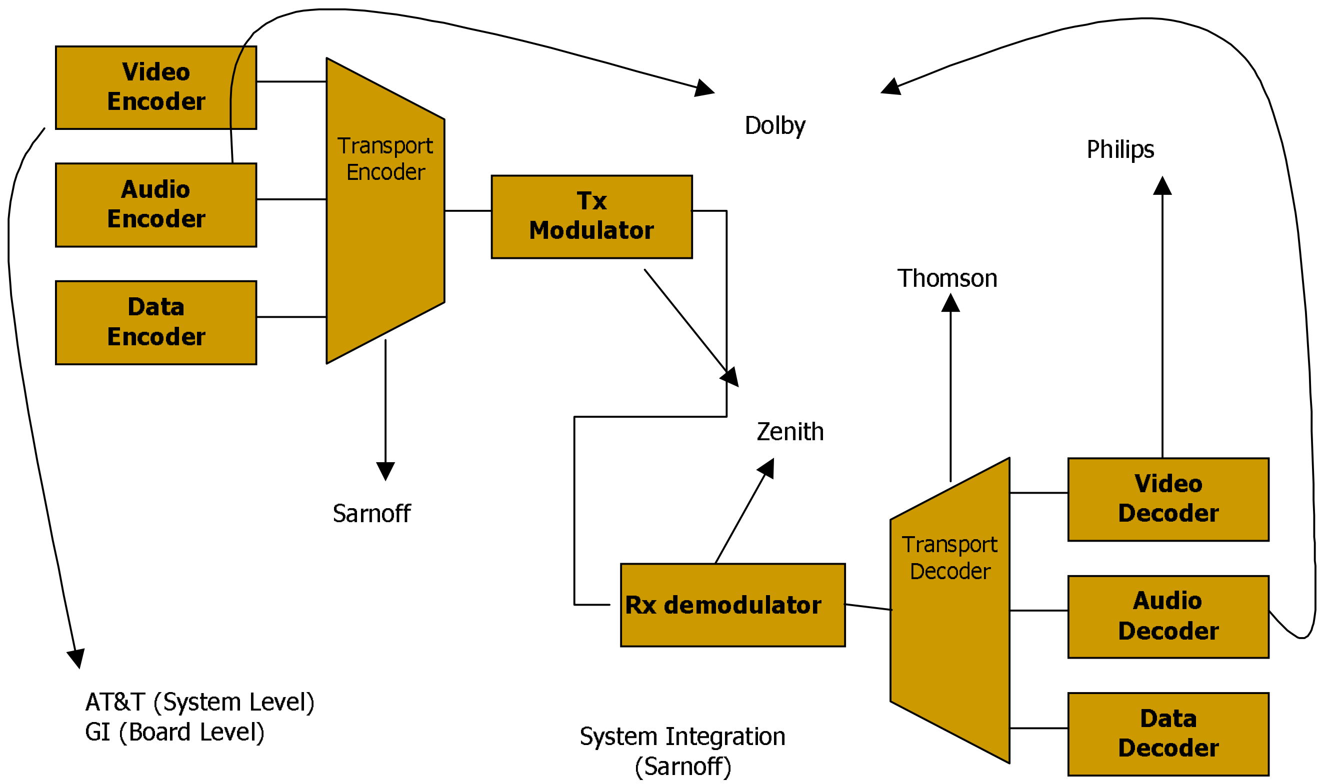

Figure 2. Technology-based labor division of the Grand Alliance

resorting to voting was often an inferior approach to resolve disagreement than persuasion, negotiation and compromise. ``Consensus" was important to them. On the one hand, this style represented the democratic, liberal trait of a specific engineering culture. However, on the other hand, it revealed the complex and unstable power relationship of an ``alliance". A lot of discussions are usually characterized by a lot of discordance and conflict.

3.1. Implementation of the System

For the build-up of the actual system, the manner of responsibility division was different. The implementation tasks were divided by subsystems. Different companies were responsible for different specific subsystems. They were no longer mixed together to work on the same technologies. Thank to the layered architecture that all the proponents decided to adopt, the labor division among companies can be drawn: AT&T was responsible for the video encoder at the system level, GI for the video encoder at the board level, Philips for the video decoder, Sarnoff for the transport encoder, Thomson for the transport decoder, and Zenith for the transmission system. The audio compression was contracted to a non-GA company-- Dolby. The whole system was integrated by Sarnoff. Figure 2 shows the layered architecture of the GA system and the corresponding companies responsible for the implementation of these layers.

The layered-based division of labor had an obvious reason: each company had technical expertise and business interest on some special technologies. GI was the first proponent of the digital video compression scheme. The packtized data format was first proposed by the Sarnoff/Thomson/Philips alliance. Zenith has produced TV modulators for years. Allocating them the subsystems that they have devoted much effort in the years of ATTC HDTV test would naturally lead the final system ``best of the best"-- a popular rhetoric of Grand Alliance [17]. And each company could gain most profit from the investment on development. Nevertheless, there was some practical advantage for such an arrangement: the company did not have to share the technologies required to build the subsystem to its team corporations. Thus video coder, transport coder, and modulator all became black boxes. The engineers from different companies only needed to work together on interfaces. The work on the contents of the black boxes were still done in isolation. In this way, the design and intellectual property were protected [2]. Notice that we should not conceive the boundary of this labor division as prior or absolute. This catalogue was not completely determined in the beginning. Neither was it settled down without dispute. At the beginning of the Grand Alliance, Zenith was only one of the two candidates for the modulation scheme, and Dolby one of the three candidates for the audio compression. The paths leading to choosing them were not straightforward.

Donald MacKenzie used the concept ``black box" to denote the undisputed, settled, opaque status of a technology. After gaining the reliance of the users on its truth and effectiveness, the technology no longer exposes its internal working mechanism. The only things visible are the input/output characteristics. Challenge and Skepticism over it were gone. In the history of the Grand Alliance, we observe that wrapping up the black box was not a wholesale enterprise. The ``black-boxness" of different technologies varied. Some technologies were consented without hesitation by all parties from beginning to end. Their acceptances were beyond doubt. Some remained highly controversial until the end of the project. Challenges came from outside as well as inside. Even the engineers did not believe the issues involved were merely technical. In more cases, however, the degree of black-boxness was in between. The technologies were distributed along a spectrum of black-boxness rather than located upon two poles. We can order the principal technologies of the GA HDTV project with decreasing black-boxness as follows:

- transport system
- video compression/decompression
- transmission/modulation
- audio compression/decompression
- scanning and resolution format

In the following subsections, we will briefly discuss the technical development and the engineering practices with respect to these technologies.

A. Transport System

The transport system groups digital data stream in packets. It defines the formats of data packets. Different types of packets-- video, audio, computer-generated data-- are multiplexed to form a single data stream. The GA transport system contains a transport layer and a packetized

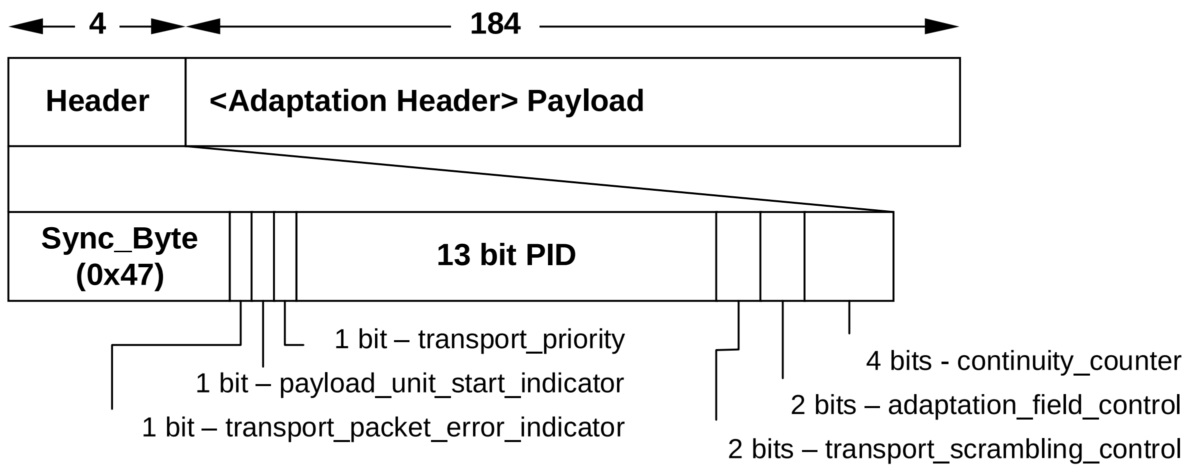

Figure 3. Transport packet format (Fig. 13, [11]).

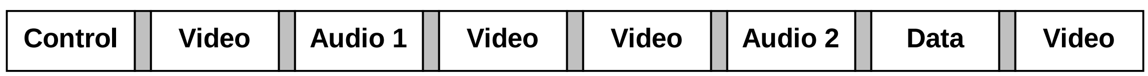

Figure 4. Example of a multiplexed transport stream (Fig. 14, [11]).

elementary stream (PES) layer. Their functions are multiplexing and synchronization [11]. Figures 3 and 4 illustrate the transport packet and an example of a multiplexed transport system.

In the Grand Alliance, Sarnoff was responsible for developing the transport encoder, and Philips was responsible for the transport decoder. The transport system was the least controversial technology. No salient dispute regarding design occurred. The arrangement that Sarnoff and Thomson were responsible for the transport encoder and decoder did not raise challenge by other proponents, either. The main reason is that the Advanced Television Research Consortium (ATRC, the Sarnoff/Thomson/Philips/NBC union) preceded the other competitors in proposing the packetized data scheme. When the ATTC test started at 1991, only AD-HDTV had its final proposal for a packetized data structure and headers and descriptors implemented. By the time when the test was finished, all the other digital HDTV proponents began to incorporate this feature into their systems [10]. It turned out that even though there were still some minor differences, the HDTV proponents basically followed their pioneer in designing the transport layer. It is reasonable to conclude that the transport system schemes available to the Grand Alliance participants did not differ too much from one another. Thus attributing the responsibility of transport system to Sarnoff and Thomson seemed unlikely to raise contention.

B. Video Compression

The video compression was conceived as the core technology of HDTV. The GA HDTV system used an MPEG-2-compatible video compression scheme that consists of Motion Compensation (MC) and Discrete Cosine Transform (DCT). The basic idea of motion compensation is to reduce the transmitted quantity of information by transmitting the differences between the original sequence of the raw images and a corresponding sequence of estimated images

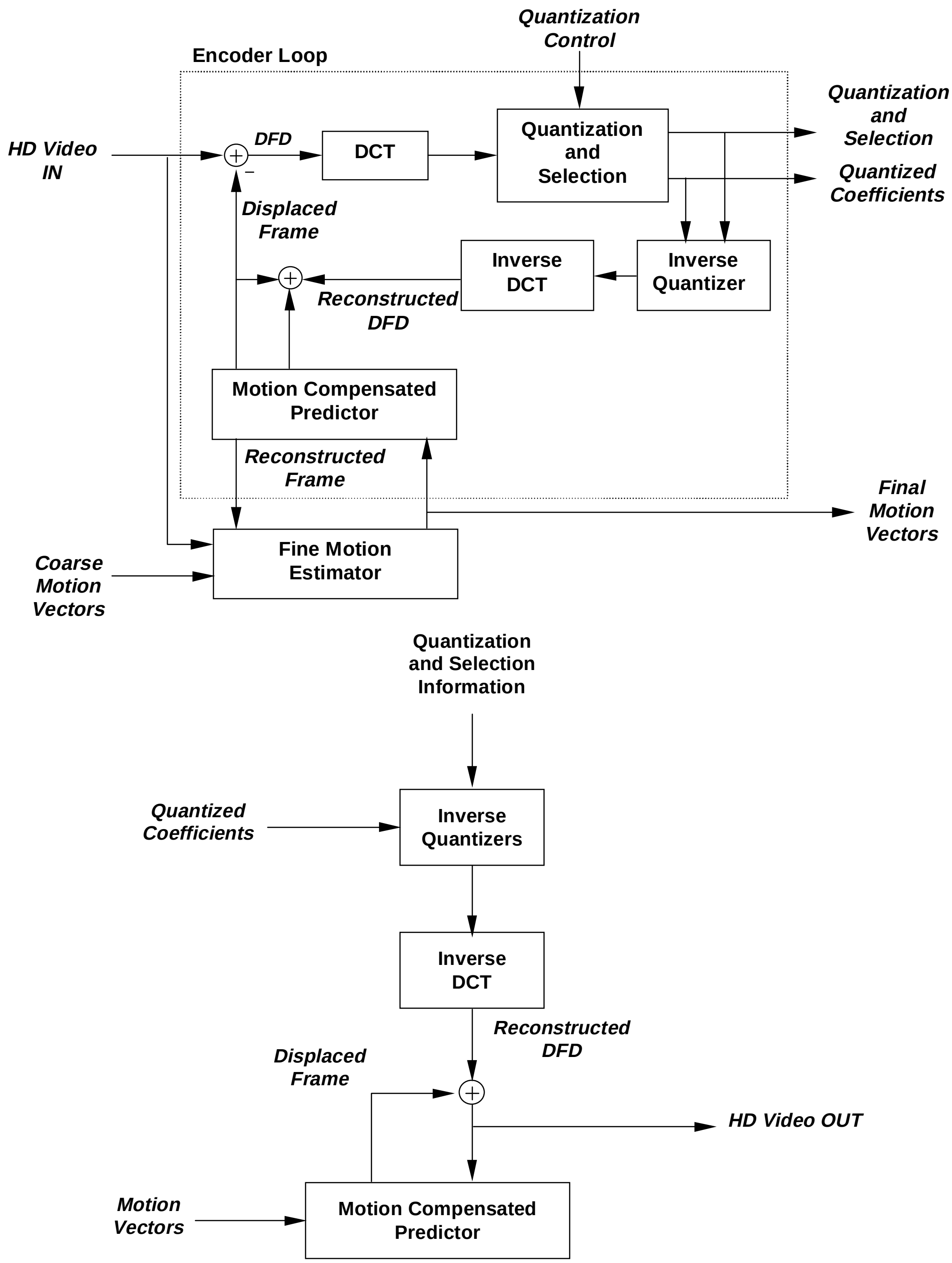

Figure 5. MC/DCT encoder/decoder loops (Fig. 6, 7, [12])

generated by a motion estimator. The concept of discrete cosine transform is to express the 2-D image data in frequency domain. Since human visual perception is less sensitive to the high (spatial) frequency components, a part of the whole set of frequency coefficients can be discarded, which further reduced the quantity of required information. Figure 5 depicts the block diagram of a MC-DCT encoder/decoder loop.

Parameter	DigiCipher™	DSC-HDTV	AD-HDTV	CCDM™
Video				
Scanning	Interlaced	Progressive	Interlaced	Progressive
Active Pixels	1408(H) $\times$ 960(V)	1280(H) $\times$ 720(V)	1248(H) $\times$ 960 (V)	1280(H) $\times$ 720 (V)
Frame Rate	29.97	59.94	29.97	59.94
Aspect Ratio	16 $\times$ 9	16 $\times$ 9	16 $\times$ 9	16 $\times$ 9
Colorimetry	SMPTE-240M	SMPTE-240M	SMPTE-240M	SMPTE-240M
Compression	MC-DCT	MC-DCT	MC-DCT	MC-DCT
Audio				
No. Channels	4/6	4/6	4	6
Sampling Rate	47.2 kHz	48 kHz	48 kHz	48 kHz
Compression	Dolby-AC	Dolby-AC	MPEG-1	MIT-AC
Service Data				
Video	17.47 Mbps	17.1 Mbps (max)	17.4 Mbps	18.88 Mbps
Audio	503 kbps	504 kbps (max)	512 kbps	755 kpbs
Data/Text	126kbps	413 kbps (max)	256 kbps	126 kbps
Transmission				
Modulation	32-QAM	2/4 VSB	Twin 32-QAM	32-QAM
Transmitted Rate	24.39 Mbps	21.0 Mbps (max)	19.2 Mbps 4.8 Mbps HP	SP 26.43 Mbps
FEC	(144,155) R/S	(167,177) R/S	(132, 152) R/S	(158,168) R/S
Equalizer Range	-2 to +24 μs	-2 to +20 μs	-4 to +8 μs (SP) -2 to +24 μs (HP)	-16 to +64 μs

Table 1. Summary of individual digital HDTV systems tested at the ATTC (Tab. 1, [11]).

From Table 1, we would discover that as early as the competing stage, all the digital HDTV proponents had the consensus of using MC-DCT. Apparently, such a similarity leads us to conclude that there would be no conflict or contention in the Grand Alliance for video compression-- their consensus had been reached from early on. Nevertheless, the category MC-DCT was by no means a proper reference to a specific technology. It is too broad. Under the generic category MC-DCT, there were a varieties of alternative approaches adopted by different

HDTV proponents. The important features of the GA video compression scheme are listed as follows [12].

Feature	Scheme	Identical with
Motion Compensation	I-B-P Frames	AD-HDTV
Video Coding	Adaptive Frame/Field	DigiCipher, CCDC
Motion Estimation	Hierarchical	DSC
Refreshing	I-frame and Progressive	
Coefficient Selection Information	Coding in Zigzag Pattern	AD-HDTV DigiCipher
DCT Coefficient Quantizer	Uniform	AD-HDTV, DigiCipher, CCDC
Forward Analyzer	Coarse Motion Vector	DSC
Perceptual Weighting		
Code Length	Variable Code Length (VLC)	All Systems

Under the apparently homogeneous mask of MC-DCT, a lot of diversities existed. Therefore a lot of detailed technical decisions had to be made by the video-compression engineers in the Grand Alliance. The above list indicated that in terms of similarity to the previous HDTV systems, the choices were quite heterogeneous. No single system was strongly favored. Does that mean the decisions were made impartially and therefore rational so that the resultant video compression technology should be ``best of the best"? Does that mean the video compression technology was a product of compromise that endeavored the balance of different parties rather than pursuing the right approach, and therefore its technical ground was not solid? We do not have answers to these questions now. Perhaps neither have the participants. The people involving in the actual engineering practices also had equivocal attitudes toward the decisions they made. Lim, for example, did believe that the GA HDTV system was supposed to be ``the best of the best". But he was also very well aware of the social constraints of the teamwork, and thus pointed out that it was about only 85 percent close to the optimum [22]. However, we know one thing: behind the above heterogeneous laundry list, there must be many discussions, persuasions and disputes. These social processes were hardly visible. In the primary and secondary sources we possess, we cannot find a dispute regarding video compression to spell out. The disputes were not politicized enough to raise the external attention. There were a lot of them. But they were settled down as pure technical issues. In other words, they were still in black boxes.

C. Transmission/Modulation System

The transmission system modulates the date stream into the 6 MHz VHF/UHF TV bands for broadcasting. Similar to the analogue transmitter/receiver, the HDTV transmission system should adequately reject the out-of-band interference, avoid the nonlinear in-band interference, and keep signal-to-noise ratio from drastic falling. In addition, a digital transmission system performs the function of error-correction coding, and channel coding that maximizes the entropy (and therefore bit rate) in terms of the statistical channel characteristics.

The decision of the transmission system cannot be quietly settled down because intense competition was present. At the early phase of the Grand Alliance, two companies proposed their own versions of the modulation systems: Zenith's 8-level Vestige Side Band, and GI's 32-level Quadrature Amplitude Modulation. As indicated in Table 1, all the other proponents (except AT&T/Zenth) followed the QAM approach of this first pioneer of the digital HDTV.

Because the decision could not be easily made by the TOG, the two systems were sent to the ATTC for testing in December, 1993. The testing results favored Zenith: it performed well. In contrast, the GI system had certain problems. Under the situation that they had difficulty in delivering their candidate transmission system on time, GI subcontracted a part of modules to another company. But this arrangement was challenged by the other GA participants (particularly Zenith) as deviation from the original agreement in which the system should be a system of GI. Moreover, the 32-QAM system had performance problems in the test. So in 1994, Zenith did not have difficulty to gain a majority vote (3 to 1) in the TOG meeting to win over GI [26].

D. Audio System

The audio system digitizes and compresses the audio signals via digital signal processing (DSP). It also provides multi-channel, stereo, and other sound effects.

The focus of the HDTV project was video rather than audio. But some of the GA participants also had interest on audio. The MIT had a well established RLE DSP group renowned for the audio signal processing. Lim was an alumni of it. Philips, as a big enterprise in consumer electronics, had good experience as well as commercial interest on stereo systems. By the time when the Grand Alliance was formed, three audio system were proposed for future use: the Dolby AC-3 system advocated by GI, Philips' Musicam, and the MIT AC. A selection must be made.

In July, 1993, the three systems were sent to the Lucas Film Laboratory at California for perception test (so called A-B test). The examiners ranked the three systems as Dolby-Philips-MIT in decreasing audio quality. But the TOG voting results did not follow the test results. In the first voting, Dolby, Philips, MIT got 1, 1, 2 votes, respectively. GI, MIT, and Philips/Sarnoff/Thomson union voted for themselves, Zenith/AT&T voted for MIT. MIT got the most number, but no one exceeded simply majority. After negotiation and discussion, they proceeded the second voting. This time Dolby, Philips, MIT got 2, 1, 0 (GI and MIT voted for Dolby, Zenith abstained). Again no one had simple majority. A further test was called for. The voting procedures was likely to repeat again. Some people started to worry about the problem of project delay. At the meeting in October 1993, the senior manager of Thomson, Michael Donahue, suggested the TOG to select Dolby. In other words, the Philips/Sarnoff/Thomson union gave up the insistence on Musicam. Therefore the dispute was eventually settled.

The contention over audio system was not resolved in a pure technical manner. Commercial interest intertwined with technical concerns. The lab test results were not the primary gauge for the decision. They were mobilized or immobilized by different parties for different purposes. The structure resembling parliamentary democracy rendered negotiation a more possible way than scientific conviction to resolve the issue. In this case, the debate was publicized. It could no longer hidden within the black box. And interestingly, it was resolved not through consensus, as in most technical decisions we have discussed so far. It was resolved through compromise. Not without regret, one party recessed from the dispute to get things down.

E. Screen Format

The HDTV screen format prescribes the scanning mode, image resolution, and frame rate. The scanning mode remained the most controversial aspect of the HDTV technology. Two scanning modes are available for display: interlaced scanning and progressive scanning. In the interlaced scanning mode, the odd numbers of horizontal lines are first scanned from top to bottom, the even numbers of horizontal lines are subsequently scanned from top to bottom. In the progressive scanning mode, the whole set of the horizontal lines are scanned altogether from top to bottom. The two scanning modes are illustrated in Figure 6. The NTSC standard (as well as other TV standards in Europe) prescribes the interlaced scanning mode. The scanning format of computer monitor screens is progressive. It is henceforth conceivable that the dispute over scanning mode would inevitably lead to a battle between the TV broadcasters and the computer industry.

The controversy over scanning mode was present at the beginning of the Grand Alliance. Among the four HDTV proponents, the AT&T/Zenith system and the MIT/GI system adopted the progressive scanning mode, while the Philips/Sarnoff/Thomson/NBC system and the GI system used the interlaced scanning mode. The debate was twofold. First, this issue was associated with priority over TV broadcasting enterprises or computer industry. For the broadcasters, an

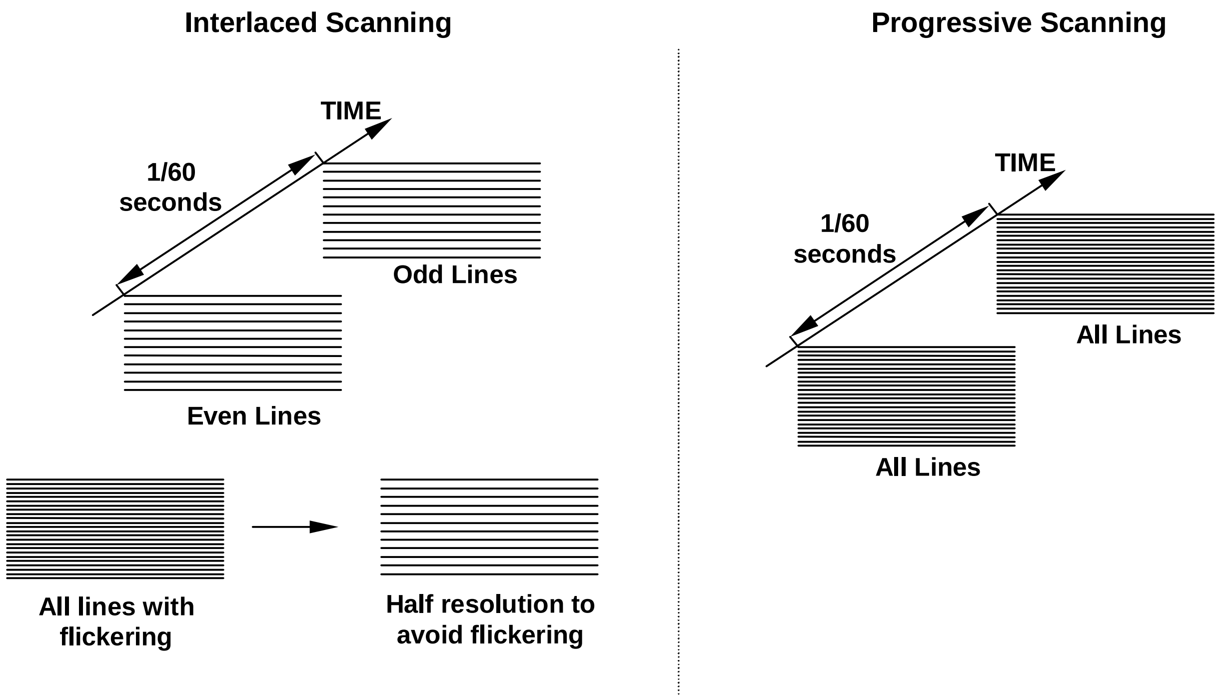

Figure 6. Interlaced and progressive scanning (Fig. 4, [Challapali et al]).

interlaced scanned HDTV as a continuation from the conventional NTSC TV remained the better choice since the current video broadcasting format did not have to alter drastically. For the proponents more closely connected with computer industry or ``envisioned" the future of HDTV to be a part of the integrated digital infrastructure, the progressive scanning mode could render a TV set a terminal station of the computer network without essential difficulty. The participants of the Grand Alliance had different positions on this issue. GI, AT&T, and Zenith did not hold a strong opinion for/against both sides. The Sarnoff/Thomson/Philips union, backed up by NBC, attempted to support the interlaced scanning mode. Jay Lim of MIT adamantly advocated the progressive scanning mode (and therefore strongly against the interlaced scanning mode) [26]. But the debate was not only a war for compatibility. It was also related to the issue of image quality. By the time when the ATTC test was finished, it was discovered that except for the fineness of the vertical structure, the image quality of the progressive scanning mode was inferior to that of the interlaced scanning mode in general [10]. That does not mean the progressive scanning is intrinsically inferior to the interlaced scanning in terms of video quality. But it does mean that the technological maturity of the progressive scanning up to 1992 was unsatisfactory. Even though it seemed more promising to an all-digital future, it had bottlenecks.

The possible technical solution of this problem was to increase the image resolution and to continue working on elaborate signal processing schemes. A progressive scanning video with very fine resolution might get rid of the problem of image quality. But it has not been realized yet. For the time being, no single screen format was far better than the others. So the proponents of the Grand Alliance reached a consensus: they would work together on both scanning modes [1]. That consensus was clearly spelled out at the screen format specification of the GA HDTV system, which is listed as follows:

Scanning Mode	Resolution	Frame Rate (FPS)
Progressive	1280 H X 720 V	60
Progressive	1280 H X 720 V	30
Progressive	1280 H X 720 V	24
Progressive	1920 H X 1080 V	30
Progressive	1920 H X 1080 V	24
Interlaced	1920 H X 1080 V	30

Here 1280 H X 720 V refers to horizontal and vertical resolutions: 1280 scanning lines and 720 pixels per line, and FPS means frame per second. In addition to the above list, the GA screen format spec had an addendum: the Grand Alliance will work toward the high-resolution progressive motion pictures. Such an addendum was partially embodied in the spec of 1920 H X 1080 V, progressive scanning images, since it had not become a reality when the standard was made. The prophecy remained to be fulfilled by itself.

The controversy over scanning mode has never vanished. From 1993 through 1996, the Grand Alliance and ACTS were constantly attacked by the representatives of computer industry and the MIT Media Lab for its unwillingness to wholly integrate with the computer monitor screen format. The FCC of the Clinton administration after 1992, which endeavored to advocate a digital National Information Infrastructure (NII), also challenged the them for the same reason. In 1996, FCC proclaimed the HDTV standard, which was almost identical to the GA specification submitted by ACATS in late 1995. In the FCC standard, the tables of screen format were taken out from the GA specification [Schreiber interview][Schreiber]. The black box of HDTV screen format was never been closed. Many engineers involved in the Grand Alliance project agreed that the issue of screen format was more political and economic than technical [12][11][1].

4. External Challenges

The Grand Alliance faced many external challenges that hindered the creation of standards. Mike Liebhold, an Apple employee and also a representative for the National Information Infrastructure, led a lobbying effort to push progressive scanning as a standard for HDTV. He argued, “In an apparent attempt to compromise, the Grand Alliance has announced a preliminary intent to support both interlaced and progressive-scan transmission. In its current form, this compromise could result in a de facto interlaced standard.” [26, p. 277] Part of the lobbying effort included sending a constant stream of letters to Congressmen, as well as the FCC. As Representative Markey, chairman of the telecommunications subcommittee, responds:

> *Has the Grand alliance fulfilled its commitment to consult with the computer industry and other involved in HDTV applications to ensure that their views are heard and their concerns are integrated? Please outline how, if at all, the Grand Alliance has fulfilled or is planning to fulfill its commitment to consult these companies or institutions. Has the Advisory Committee on Advanced Television Service included representatives of these industries in its review process.* [26, p. 278]

Wiley was pressured into creating a new committee, “an interoperability subgroup,” that dealt with listening to other industry concerns regarding HDTV. The growth of the computer industry and its development of high-resolution displays also added to this push for a complete digital HDTV system. The Digital Open High Resolution Systems group (DOHRS) in the Center for Technology Policy and Industrial Development at MIT studies technical, economic, and policy challenges to open interfaces for high resolution systems. Their involvement with HDTV is to participate in the political process of the standardization of a digital HDTV system with progressive scanning [6].

The Grand Alliance dealt with the FCC’s move to digital standard television. With the maturity of digital TV technology, the broadcasters were aware that by dint of the digital transmission they can accommodate the standard TV signals of several channels into a single 6 MHz band. This means they now had more channels for the given bandwidth. Therefore, the broadcasters became more interested in exploring the digital technology of the standard-format TV, rather than the digital HDTV. This was a crisis for the Grand Alliance since to ensure the support from the broadcasters was important to the success of their standard. The way they resolved this crisis was to persuade the broadcasters that by compressing standard TV signals, they might have the risk of their channels being taken and relocated by the FCC. To make full use of the bandwidth by committing to the high definition digital TV was a good way to secure the whole bandwidth. Thus, the broadcasters recognized this new problem and had to deal with concerns over losing the second channel that was designated to them by the FCC. This loss was a possibility because “it could be that if you want to do only standard-resolution programs, the FCC will give you only

4 megabits and auction the other 16 megabits . . . The beautiful aspect about high-definition is that it takes up the whole 20 megabits.” If television stations broadcast high-definition programs, there would left no space to be auctioned off. [26, p. 324]. This persuasion worked in the GA’s favor in terms of having the broadcasters push the FCC to establish a standard for HDTV.

Another external challenge to the Grand Alliance concerned the transmission technology. The modulation scheme designed by the proponents of the Grand Alliance, either VSB or QAM, was a particular version of Amplitude Modulation (AM). While AM has been the standard technology for transmitting NTSC signals, it was not the only approach for transmitting digital HDTV signals. At the same time, when the pre-Grand-Alliance proponents were developing their own HDTV systems, a different modulation scheme-- known as the Coded Orthogonal Frequency Division Multiplexing (COFDM)-- emerged from academia. Unlike AM that possesses a single carrier, COFDM dynamically allocates the video signals onto different carrier frequencies. This new multi-carrier modulation scheme was strongly advocated by William Schreiber, the former director of the MIT ATRP group, who made a good effort to promote the visibility of this technology to the participants of the HDTV plan. In 1992, he held a conference at MIT promoting COFDM. He invited the FCC ACATS and those companies who had their systems tested at the ATTC. But no one came [3]. Despite Schreiber's support of the project, COFDM was never seriously considered as a candidate for the transmission technology throughout the development phase of the Grand Alliance. But the “noise” was salient enough such that the Grand Alliance and the ACATS could not totally ignore its existence. From 1994 to 1995, a so-called COFDM-Limited Liability Corporation (COFDM-LLC) proposed an ATV COFDM modem to the ACATS. The Expert Group responsible for reviewing this proposal finally concluded that “the modem presented by the COFDM-LLC is not ready for testing at this time”, and it “did not demonstrate the superiority of COFDM over VSB for the majority of markets”. Nevertheless, the ACATS also noticed that “COFDM technology continued to be developed in Europe and Asia” [8].

5. MIT’s Contribution

In the eight-year span of pushing for FCC approval of HDTV standards, MIT contributed to the process in two major ways. First, independently from April 1987 to June 1995, MIT had filed 18 patents relating to HDTV ranging from high-level digital television systems design to highly specialized motion estimation method and different video encoding methods. MIT is the owner of these patents developed at the Advanced Telecommunications and Signal Processing Group in the Research Laboratory of Electronics (RLE), directed by Professor Jae S. Lim. Through our findings, it was not especially clear which parts of these patents were adopted in the final digital television standards. “MIT did not build any specific part in this project. (GA) Lim participated in the technical oversight group and hence pronounced his voice (which was equivalent to MIT’s) in the decision making.” [1] “We contributed mainly in the overall design of the HDTV system, it is not beneficial for us (MIT) to actually make any component because we don’t have enough resources available.” [4]

Another contributing group to the HDTV effort was what Joel Brinkley named the *MIT guerrillas*. The MIT guerillas included some members of the Program on Digital and Open High-Resolution Systems. In short, they acted along the same lines as Mike Leibhold, and helped push for a standard that is aimed at disseminating cross-country, cross-government agency, and cross-academic disciplines. However, they chose to participate in the process outside the official arena of ACATS, and instead tried to use their political resources. Their lobbying efforts consisted of standard White House lobbying, giving demos to high-level executives, and increasing awareness of what is available to the general public. These initiatives were important to the computer industry because they wanted the entire system to be digital and, therefore compatible with the future of digital communication.

Conclusion

The story of the HDTV was a complex interaction among different players with different interests. Political and economic factors were as important as technical factors in shaping the story. Sponsored by the TV broadcasters and the US government for different reasons, the initial call for HDTV started as a political move that created a need for something still absent in the market. But then a technological milestone-- the all digital TV-- was accomplished in the middle of the game. This ``engineering revolution" became a principal event that transformed a modest advisory committee into a major coordinator of a big technical project, which was never expected by its first incubators-- the TV broadcasters. The history of the Grand Alliance, as a consequence of this engineering revolution, was also registered with politics. But it was a different kind of politics: the power relations among the participating companies. Here we observed the complexity of exercising heterogeneous engineering in a technical project where multiple participants with various corporate or personal interests were involved. It was also discovered that not all the technical decisions in this project were equally convinced (or unconvinced) by the engineers. Some were successfully wrapped up as black boxes. Some never became black boxes.

References: Primary

[1.] Reitmeier, Glenn, telephone interview, November 23, 1999.
[2.] Smith, Terrence, e-mail interview, November 24, 1999.
[3.] Schreiber, William, interview, November 10, 1999.
[4.] Lim, Jae, interview, November 4, 1999.
[5.] Martinez, Dennis, telephone interview, November 22, 1999.
[6.] McKnight, Lee, interview, November 24, 1999.
[7.] The Grand Alliance, Grand Alliance HDTV System Specification, Version 2.0, December 7, 1994. (http://vera.inforamp.net/~poynton/Poynton-ga-hdtv.html)
[8.] Advisory Committee on Advanced Television Service, Federal Communications Commission, *Advisory Committee Final Report and Recommendation*, November 28, 1995. (http://www.atsc.org/papers/a_cats/finalrpt.html)
[9.] Advisory Committee on Advanced Television Service, Federal Communications Commission, “ATV system recommendation,” *IEEE Transactions on Broadcasting*, vol. 39, no. 1, pp. 2 - 245, March 1993.
[10.] Hopkins, Robert, “Choosing an American digital HDTV terrestrial broadcasting system”, *Proceedings of the IEEE*, vol. 82, no. 4, pp. 554 - 563, April, 1994.

[11.] Challapali, Kiran, Xavier Lebegue, Jae S. Lim, Woo H. Paik, Regis Saint Girons, Eric Petajan, Vinay Sathe, Paul A. Snopko, and Joel Zdepski, “The Grand Alliance system for US HDTV”, *Proceedings of the IEEE*, vol. 83, no. 2, pp. 158 - 174, February, 1995.
[12.] Petajan, Eric, “The HDTV Grand Alliance system”, *Proceedings of the IEEE*, vol. 83, no. 7, pp. 1094 - 1105, July, 1995.
[13.] Kaplan, Karen, “MIT proposes national standard for digital TV”, *The Tech*, April 3, 1992. (News release)
[14.] MIT News Office, “MIT, General Instrument joins in HDTV Alliance”, *MIT Tech Talk*, February 6, 1991. (News release)
[15.] Advisory Committee on Advanced Television Service, Federal Communications Commission, “HDTV system recommended to FCC”, November 28, 1995. (News release) (http://www.fcc.org)
[16.] Advisory Committee on Advanced Television Service, Federal Communications Commission, “Digital HDTV test results”, November 28, 1995. (News release) (http://www.fcc.org)
[17.] Basile, Carlo, Cavallerano, Alan, Deiss, Michael, Keeler, Robert, Lim, Jae, Luplow, Wayne, Paik, Woo, Petajan, Eric, Rast, Robert, Reitmeier, Glenn, Smith, Terrence, Todd, Craig, “The U.S. HDTV standard: The Grand”, *IEEE Spectrum*, vol. 32, no. 4, pp. 36 - 45, April 1995.
[18.] Bell, Trudy, “The HDTV test kitchens”, *IEEE Spectrum*, vol. 32, no. 4, pp. 46 - 49, April 1995.
[19.] RLE Progress Reports, 1988 - 1995.
[20.] MIT-owned patents on HDTV technology (18 items).

References: Secondary

[21.] Fleisher, Dorothy, “Changing the image of broadcast technology: RLE's Advanced Television and Signal Processing Group”, *RLE Currents*, vol. 10 no. 1, pp. 1 - 11, Spring 1998.
[22.] “Faculty profile: Jae S. Lim”(interview), *RLE Currents*, vol. 10 no. 1, pp. 14 - 17, Spring 1998.
[23.] Neil, Suzanne, Lee McKnight, and Joseph Bailey, “The government's role in the HDTV standards process: model or aberration?”, *Standards Policy for Information Infrastructure*, edited by Brian Kahin and Janet Abbate, pp. 276 - 288, MIT Press, 1995.
[24.] Kuhn, Kelin, “HDTV television - an introduction” (http://www.ee.washington.edu/conselec/CE/kuhn)
[25.] Lim, Jay, “Digital television: here at last”, Scientific American, pp. 78 - 83, May, 1998.
[26.] Brinkley, Joel, *Defining Vision: The Battle for the Future of Television*, Harcourt Brace, New York, 1997.
[27.] Flaherty, J. A., “DTV Reinventing broadcasting, a perspective on digital TV and HDTV” (http://mptv.org/dtv1.htm)
[28.] Rice, John F., *“HDTV: The Politics, Policies and Economics of Tomorrow’s Television*”. Union Square Press, New York, 1990
[29.] Beltz, Cynthia A., “*High-Tech Maneuvers: Industrial Policy Lessons on HDTV*”. The AEI Press, Washington D.C., 1991.