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OPEN STANDARD GIGABIT ETHERNET LOW LATENCY VIDEO DISTRIBUTION ARCHITECTURE

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ABSTRACT

Curtiss-Wright has developed an open-standard approach to low latency digital video distribution, incorporating VICTORY .specifications and other open standards, including Motion JPEG 2000. The paper presents various application definitions, parameters, and reference architectures, demonstrating the applicability to ground vehicles, and suggesting additional specifications and open standard to include in VICTORY.

INTRODUCTION

Digital Video Distribution is widely adopted in the telecommunications and broadcast industries. The technologies and methods for capturing, distributing, securing, recording, and displaying digital media have seen significant industry wide investment and advancement over the last two decades. Application of these technologies to the military ground market, specifically for situational awareness and low-latency applications (e.g. driving) have become realizable, and are well supported by the adoption of the VICTORY Architecture and Specifications.

Curtiss-Wright has developed an advanced, open system architectural approach to Vehicle Electronics, based on our vast experience in providing military electronics to many programs for ground, sea, and air platforms. Additionally, for the past several years we have been performing research into network centric approaches specifically for Heavy Brigade Combat Team (HBCT) Vehicle Electronics. This experience has provided CW with a unique understanding of key architectural concepts which provide for highly successful implementation of specific Vehicle Electronics suites to meet Ground Combat System program and platform requirements.

Specifically, the digitization and distribution of analog low-latency video using the open standard Motion JPEG2000 protocol over Gigabit Ethernet was demonstrated in comparison to open standard MPEG2 and MPEG4 temporal video compression protocols. This paper builds upon that experience to show open-systems, non-proprietary approaches to digital video distribution throughout a vehicle meeting multiple video application needs. An analysis of image resolutions, frame rates, video bandwidth, various compression algorithms, compression ratios, latency, and determinism against Gigabit Ethernet capabilities and constraints will be provided. A reference architecture for Digital Video Distribution for modern ground vehicles will be presented, utilizing the VICTORY Architecture and Specifications.

At the end of the presentation, the audience will understand how to evaluate video distribution needs against the capabilities of the vehicle’s VICTORY Databus, and in what circumstances an alternative approach would be required.

TRADITIONAL PERCEPTIONS OF VIDEO DISTRIBUTION

Video Distribution has the reputation of being a difficult and demanding task. With legacy analog video distribution, problems are related to the degradation and phasing of the analog signal, requiring careful control of system elements such as transmission line impedances, analog splitting and mixing, distribution amplification, and phase adjustments such as time base correction and time code locking. With the advent of point-to-point professional digital video standards, such as Serial Digital Interface (SDI) and consumer focused standards such as High Definition Multimedia Interface (HDMI), and number of the problems of analog distribution are addressed. Signal quality is generally not a concern versus cabling; however, distribution and mixing of signals requires a more complicated set of building blocks. With these newer standards small scale multi-source / multi-display systems are achievable, but absolutely do not scale well given the cost of various building blocks. While the use of these mainly point-to-point digital video standards is appropriate for a small number of highly tailored professional production and broadcast infrastructures to support the television industry, a different approach is required for the higher volume SWaP-C constrained market of ground vehicles. This approach, more common to the distribution of video in consumer, industrial, and Internet spaces involves the use digital video on an Ethernet Network, generally using Internet Protocol and a number of various standards by which to encode / decode and stream video.

The distribution of digital video typically has three major areas of concern and optimization – quality, latency, and bandwidth.

Quality

The quality of digital video is dependent on a number of factors relating to elements of the system from origination at the sensor to eventual display. Chief of these are resolution, pixel bit depth, and frame rates. When including various compression standards, the quality of the compression encoding and decompression decoding standards (and implementations) are extremely critical. Finally, in a distribution system in which underlying network quality (drops, congestion, packet sequencing) is of issue, resilience to these varying conditions is also of importance.

Latency

The time it takes for an image to travel from the origination sensor to display can be of concern, depending on the application. This “glass-to-glass” latency between the lenses of a sensor to the glass of a display device is critical for the usability of the video in various applications, and completely irrelevant in others.

Bandwidth

Fundamental to the transmission and storage of any digital data is the requirement for bandwidth. Video is a special case in that often in Video Distribution, the concept of live streaming is involved, in which the video distribution system must support and accommodate uninterrupted video viewing, with or without the concept of buffered playback. Fundamentally, if the required bandwidth of the video exceeds that of the infrastructure, then unbuffered live viewing is impossible. Nevertheless, not all video distribution applications require live viewing, allowing the buffering of video to be utilized.

APPLICATION DEFINITIONS

The discussion of quality, latency, and bandwidth clearly demonstrate the need for well-defined and constrained video distribution applications as a foundation for any analysis, optimization, and architecture development. A video distribution system may support a single application type, or multiple types. Fortunately, digital video distribution on Ethernet using open standards can support multiple approaches and optimizations to meet various applications.

Various applications for video distribution are described below, with emphasis on key performance parameters, and delineation between live (qualitatively “as it happens”) video and playback of stored video (qualitatively “in the past”).

Sharing

One of the simplest applications is that of sharing video. Essentially, this is allowing live video to be viewed at multiple displays, or stored video to be played back at multiple displays.

In the case live sharing, the application intent is to allow multiple viewers to see the same thing at the same time, essentially “see what I see” to provide a common and shared experience. Excluding the concept of many viewers for one display, sharing requires that N viewers (or potential viewers) need to be provided the video at N displays.

Although a straightforward application, not all parameters are uniquely constrained. In a live sharing case, the quality and latency of the shared video to each display must be clearly defined for each user in order to guide bandwidth requirements. The simplest approach is that all users receive an identical set of parameters. More complicated is the concept of some users receiving a higher performance (quality, latency) stream, while others receive a differently optimized stream given their specific needs.

In the case of stored sharing, the application intent is to let multiple viewers independently view stored video asynchronously. This is a more general case of live sharing, in which the parameters for each user are determined per user, and latency is no longer of concern (video is no longer live).

Awareness

Distribution of video for awareness of various live events is an important application in which the end users must be able to see video sourced by one or many sensors in a functionally real-time sense. This application is best exemplified by a set of live security or other real-time monitoring systems, including 360 degree Situational Awareness systems. The users need sufficient quality to properly see and visually understand events with low enough latency such that the observed events are nearly real-time (within seconds), allowing immediate reaction if warranted.

In this case, often the user is presented with a merge of many sensors into single unified user interface with well controlled image arrangement (from tiled images to stitched and merged images). Consistent latency is important in order to assure that the unified user interface is temporally coherent. Scaling of image quality is useful as well, allowing a particular sensor of interest to be viewed at a higher resolution on demand. The overall bandwidth required for such as a system is general a sum of the number of sensors; however, this can present a bottleneck at the user interface itself, both for the distribution network and the end user (information overload). Various management strategies are required to ensure an awareness system is manageable.

Bandwidth Efficiency

Often latency and quality are completely dependent on overall bandwidth available. This is common in various wireless connections, where overall bandwidth is severely restricted, although this is also common in wired infrastructures where the overall quantity of video streams is high.

The case fundamentally has two usage scenarios – live stream or buffered streaming. In the first case, the video's bandwidth requirements must be essentially at or below the available network bandwidth. This ensures that video (whether of live or recorded events) is streamed to the viewer with an absolutely minimum of delay between viewing request and streaming starts. This type of usage scenario is common for applications such as video chat. The second use case allows for non-trivial buffering of the video before distribution, allowing a video which exceeds the bandwidth of the channel to be delivered. The larger the disparity between the two bandwidths (required and available), the larger the buffer needs to become, and the longer the delay between request of video and streaming starts. Due to the use of buffers calculated on the expected total run-length of the video, this is not well suited to applications such as video chat, but instead applications such as distributing finite length video clips on demand in a user environment which tolerates larger buffering in exchange for better quality.

Archival

Quality is absolutely the highest priority in archival when such need is critical for reproducing the original video as best as possible. Latency is essentially irrelevant encoding a stored source, but critical in the archival of live video sources, since the encoding process must absolutely keep up with the frame rate of the source, lest frames be dropped. This does not mean that the encoding process needs to be encode a single frame in the time of a single frame, but that the overall encoding process from frame input to encoded frame output operates that the same or better framerate. The encoding of a single frame can take any length of time, as long as the process is pipelined. Bandwidth, although important, is generally a consideration only for the recording system's storage capacity and fundamental data interface links. Various methods to scale recording capacity and interface link capacity, such as Redundant Array of Independent Disks (RAID) and scalable filesystems mitigate the various bandwidth issues associated with Archival use cases.

Control

The most demanding video distribution application is that of real-time control. Video distribution latency impacts the performance of the control loops, whether or human or machine. Depending on the control application, quality can be just as important. Tracking applications (such as targeting) are dependent on both the latency and the quality in order to provide performance in both responsiveness and accuracy. On the other hand, applications such as driving may allow quality to degrade marginally given that far-field image quality is not as important as near-field, such as obstacle avoidance. Although bandwidth is often considered to be far secondary in control applications, excessive bandwidth is not absolutely necessary.

PARAMETERS AND METRICS

The parameters and metrics for video distribution are very straightforward, and provide the mathematical basis for the qualitative applications descriptions. These are defined below, along with descriptions of various technologies impacting the architecture designs. Readers familiar with the terminology can easily skip forward to Architectures descriptions.

Frame sizes, depths, and rates to bandwidth

Video is fundamentally described by three parameters:

- Frame Size – expressed in Width and Height, measured in Pixels (or columns of pixels by rows of pixels).
- Pixel depth – expressed in total number of Bits per Pixel
- Frame Rate – expressed in Frames per Second

The required Bandwidth for an uncompressed video stream is easily calculated by multiplying the three parameters together:

Frame Rate x Width x Height x Pixel Depth = Bandwidth

For example, a standard definition Frame Rate is 30 frames per second (fps), the Frame Size is 640 x 480 pixels, by 24 bits per pixel (bps), the overall Bandwidth required is calculated below, showing intermediate calculations for clarity:

30 fps x (720 x 480) pixels/frame x bps =
30 fps x 345600 pixels/frame x 24 bps =
30 fps x 8,294,400 bits/frame =
248,832,000 bits/second = ~250 Megabits/second

A typical high-definition video example is 60fps of 1920x1080 with 32 bps. The resultant Bandwidth is:

60 x 1920 x 1080 x 32 = 3,981,312,000 = ~4Gbps

For comparison, wired Ethernet ranges from 10Mbps to 10Gbps, wireless Ethernet standards range from 11Mpbs to 150Mbps or higher and typical radio links are 100kbps or lower. Given this comparison, it is apparent that the use of uncompressed video may or may not be reasonable depending on the type of video and the distribution application.

Pipelines and Latencies

Latency in video distribution is best understood when video pipelines are understood. Although the fundamental unit of video is a single pixel, most pipelines operate on a per frame basis. Both frame based and pixel based latencies will be discussed. Latency in the pipeline is found in multiple locations:

- Sensor latency – from the glass of the sensor to the internal electronics, a fundamental latency exists based on the capture frame rate. Assuming the sensor operates at X Frames / second, the overall time to capture an entire frame is 1/X seconds. For example, a frame rate of 30 fps results in a frame period of ~33 milliseconds. Pixel based calculations are similar.
- Encoding latency – whether compressed or not, the amount of time required to take a single frame and encode it for transmission is the encoding latency. Assuming the frame can be encoded without any dependency on successive frames, then the encode latency is dependent on the encoding process time. Note that the encoding may be pipelined, such that an encoding can take longer than a fundamental frame period. For example, an encoding process which takes 5 frame periods means that the first frame out of the process will have an overall encode latency of 5 frames periods, and it is assumed that encode process provides a pipeline such that the 2^{nd} through 5^{th} frames are also in the pipeline, although a number of steps behind the 1^{st} frame.
- Network latency – once an encoded frame is ready, network transmission latency is involved, incurred by any sort of data on the network.
- Decode latency – similar to encode latency, the amount of time to transform encoded data back into frame.
- Display latency – similar to sensor latency, this is the amount of time required to product a frame to the display glass from the input data, and is can be dependent on the frame rate of the device itself. Pixel based calculations are similar.

Of note with display latency is the concept of single or double buffering. In single buffering, any changes to pixels are done directly in the video memory which is used to drive the display. This is the fastest way to produce a change on the display, taking no longer than the total number of pixels in the display minus 1 to show up. A side effect of this is that display can show pixels from two very different frames at the same time, resulting in a tearing effect.

On the other hand, double buffering means that all pixel updates are done to a region of memory which is currently off-screen (back buffer), leaving the on-screen memory (front buffer) untouched. When the display has finished its raster of the front buffer and is about to start the next raster pass (Vertical Sync), the display is pointed to the back buffer containing all the newly updated pixels, which now becomes the front buffer, and the old front buffer becomes the back buffer for the next frame.

For clarity, the Latencies are shown in Figure 1.

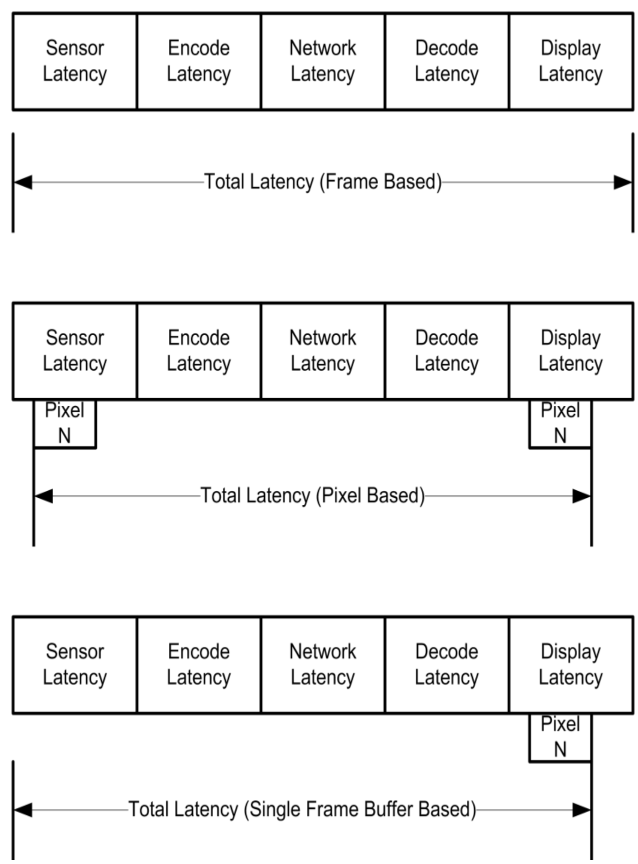

Figure 1: Total Latencies

Compression Formats

In order to reduce the overall bandwidth required, various data compression schemes are used, each with various benefits and drawbacks. Regardless of the various particular formats, key common techniques and approaches are used, as described below.

Lossy and Lossless

Lossy compression techniques involve reduction in data such that quality is reduced from the original as part of the compression. Maximum compression is achieved using lossy techniques. The amount of loss produces various compression artifacts in the form of decreased resolution or added noise, which may or may not be perceptible to the viewer. Lossless compression techniques involve compressing the data in such a way that all data is 100% recreated exactly bit-for-bit during the decompress process. Lossy compression which is of high enough quality to appear lossless to the viewer is considered imperceptibly lossless.

Constant or Variable Bit Rate

An uncompressed video stream is by its nature Constant Bit Rate (CBR) in that the bit rate does not change over time. Compressed video streams can be either CBR or Variable Bit Rate (VBR). With various compression algorithms which trade the amount of loss versus bit rate, allowing VBR provides flexibility to the algorithm to allocate more bits or fewer bits per frame depending on the complexity of the content and resultant difficulty in compressing it, e.g. a frame of a single color versus a frame of essentially random patterns and colors. The compression algorithm parameters are typically bounded (e.g. no greater than 512Kbps, no less than 128Kbps), and instantaneous bitrate varies across time. On the other hand, to maintain absolute determinism in the system, CBR allows quality to slide up and down in order to maintain the constant bit rate (e.g. 384Kbps).

Intra-coded and Inter-coded (Predicted and Bidirectional) Frames

Compression formats which compress data within a single frame independent of the content of previous and successive frames are considered Intra-coded frames. On the other hand, formats which use and compressed the content of a series of frames (or Group of Pictures) in order to gain greater coding efficiency use Inter-coded frames, meaning frames which are mathematically dependent on the frames around it. Two types of Inter-coded frames are defined, Predicted (P) Frames and Bidirectional (B) Frames, often referred to as "Between" Frames. P-Frames are mathematically dependent on the difference from previous I-Frames and P-Frames. B-Frames are mathematically dependent on the differences between previous I-Frames and P-Frames as well as future I-Frames and P-Frames.

Compression formats using Inter-coded P and B frames are generally termed temporal compression formats, since they utilize information over time to provide compression. The difference between the two approaches is shown in Figure 2.

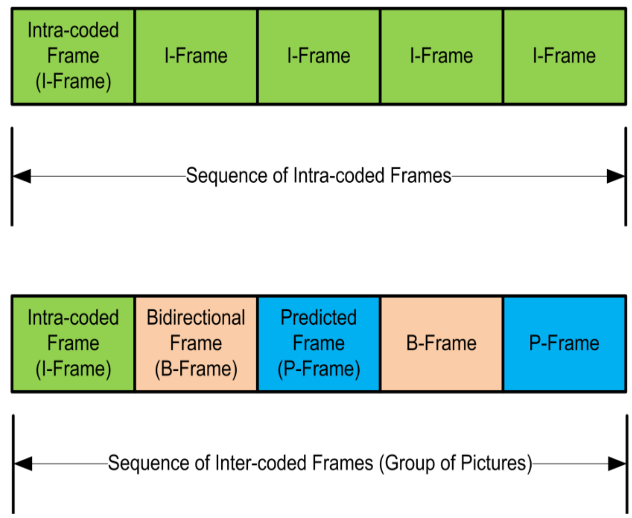

Figure 2: Encoding Sequences

Latencies

With regard to encode and decode latency, intra-coded frames can have latencies less than a single frame period. Inter-coded P-Frames can also have latencies less than a single frame period; however, the encode and decode systems must maintain memory of previous frames for calculations. On the other hand, inter-coded sequences using B-Frames require a coding latency at least as long as the maximum run of B-Frames, since these frames are calculated from either I for P frames from either end of the sequence. For the Group of Pictures in Figure 2, the minimum encoding and decoding latency is at least 3 frames, since the 2nd frame (B-Frame) is dependent on the 1st frame (I-Frame) and the 3rd frame (P-Frame). This distinction is extremely important to various video distribution architectures.

Uncorrected Error Resilience

Video streams based on intra-coded frames are fundamentally more resilient to errors since an error burst is only able to affect the single frames of data it alters. On the other hand, errors in video streams using inter-coded P and B-frames can significantly affect a large number of frames since the single error burst may alter information required by a number of frames in both the past and future.

Bandwidth Examples and Comparisons

The following examples provide general understanding of the ranges of capabilities for various inter-coded temporal and intra-coded (non-temporal) compression schemes, noting that these include various accompanying audio (roughly 10% of bitstream) and transport streams.

- Standard Definition (720x480 @ 30fps @ 24 bpp, uncompressed rate of ~250Mbps)
  - DVD with MPEG-2 compression is VBR limited to 9.8Mbps, typically around 2-5 Mbps (~50:1 compression)
  - Downloaded with MPEG-4 compression (e.g. iTunes), typically 1.5 Mbps (~150:1 compression)
  - Visually Lossless Motion JPEG2000, CBR 14Mbps (~18:1 compression)
  - Mathematically lossless MJPEG2000, CBR 45Mbps (~5:1 compression)
- High Definition (1920x1080 @ 60fps @ 32 bpp, uncompressed rate of ~4Gbps)
  - Over-the-air (limited to 30fps) MPEG-2 CBR at ~19Mbps, wired (includes 60fps) at CBR ~38Mbps (~100:1 compression)
  - Blu-ray Disc with MPEG-2 or MPEG-4 compression is VBR limited to ~50Mbps, typically in ~15-35 Mbps (~150:1 compression)
  - Downloaded with MPEG-4 compression (e.g. iTunes), typically 5Mbps (~800:1 compression)
  - Visually Lossless (Motion JPEG2000, CBR ~100Mbps (~40:1 compression)
  - Mathematically lossless MJPEG2000, CBR ~600Mbps (~7:1 compression)

In the case of Motion JPEG2000, a more advanced encoding technique using wavelet transforms, all frames are intra-coded using JPEG2000 which means maximum latency is significantly less than MPEG-2 or MPEG-4 temporal codecs if using a GOP including B-frames. Additionally, intra-coded frames result in better error resilience from a data standpoint, but above and beyond this, JPEG2000 under errors results in a softened (blurry) picture, whereas MPEG-2 and MPEG-4 frame errors result in lost blocks of the frame itself.

One benefit of MJPEG2000 over MPEG-2 and MPEG-4 is the ability for a single stream to be transmitted and decoded at multiple different data rates and resolutions, whereas MPEG-2 and MPEG-4 typically need separate streams at different encoding rates.

A guide to sizing networks for different formats, assuming 80% network throughput (e.g. UDP), resulting in 80Mbps or 800Mbps on 100Mbps and 1Gbps networks, along with Codec Latencies, is shown in Table 1.

Table 1: Video Formats, Bitrates, and Codec Latencies

Format	Bitrate (Mbps)	Streams / 100Mbs	Streams / 1Gbps	Codec Latency
SD Uncompressed	250	0	3	Sub-Frame
SD MPEG-2	5	16	160	Multi-frame
SD MPEG-4	1.5	53	533	Multi-frame
SD MJPEG2000 Visually Lossless	14	5	57	Sub-Frame
SD MJPEG2000 Lossless	45	1	17	Sub-Frame
HD Uncompressed	4000	0	0	Sub-Frame
HD MPEG-2	38	2	21	Multi-Frame
HD MPEG-4	25	3	32	Multi-frame
HD MJPEG2000 Visually Lossless	100	0	8	Sub-Frame
HD MJPEG2000 Lossless	600	0	1	Sub-Frame

Similar to MPEG-2 and MPEG-4, Motion JPEG2000 is an open standard, defined in ISO/IEC 15444-3 and ITU-T T.802, and is widely adopted for Digital Cinema and other high quality applications, including astronomy, film archival, and national imagery uses.

ARCHITECTURES FOR APPLICATIONS

The following presents core reference architectures for the various applications in the context of mobile platforms.

Sharing

The Reference Architecture for Sharing applications is shown in Figure 3:

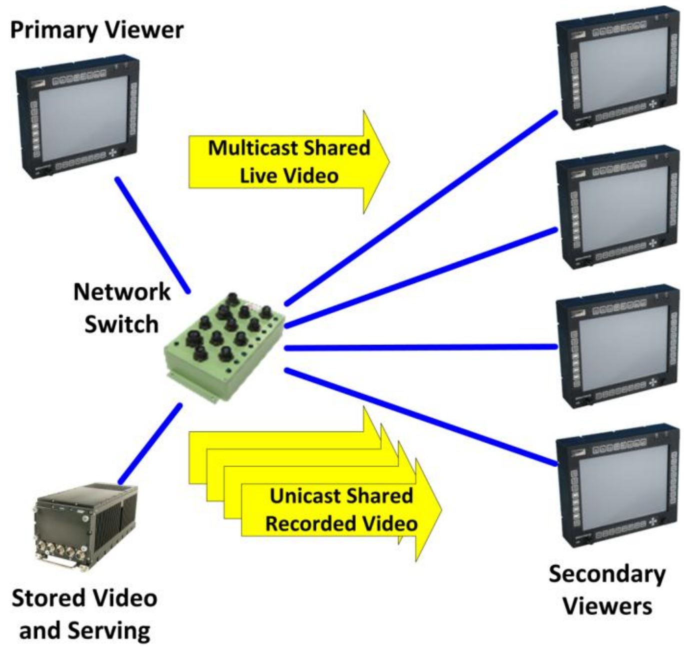

Figure 3: Reference Architecture for Sharing Applications

Key Elements of this architecture:

- Compressed and multicast video from a mirrored display for secondary viewers, where quality is optimized to enable a minimum of compression artifacts.
- The multicasting preserves bandwidth from the primary display.
- The stored sharing is fundamentally unicast since the requesting viewers aren't necessarily requesting the same video and the same time. Stored sharing can utilize bandwidth conserving buffering to meet the channel capacities.
- For additional scalability of the stored video server, additional network interfaces can be provided.

With Gigabit Ethernet, this architecture can easily stream up to 32 HD compressed streams, as shown in Table 1.

Awareness

The Reference Architecture for Awareness applications is shown in Figure 4:

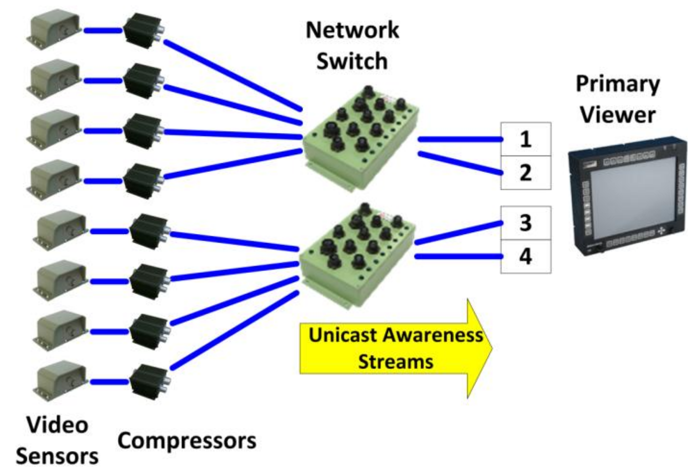

Figure 4: Reference Architecture for Awareness Applications

Key Elements of this architecture:

- Uncompressed video from sensors is compressed prior to entering the network as unicast streams.
- Multiple physical network connections to the primary viewer can be used for scalability
- Multiple physical networks can be used for scalability

With Gigabit Ethernet, this architecture can easily integrate up to 32 HD compressed awareness streams with multi-frame latency, or up to 8 HD compressed awareness streams with sub-frame latency, as shown in Table 1.

Bandwidth Efficiency

The Reference Architecture for Bandwidth Efficiency is shown in Figure 5:

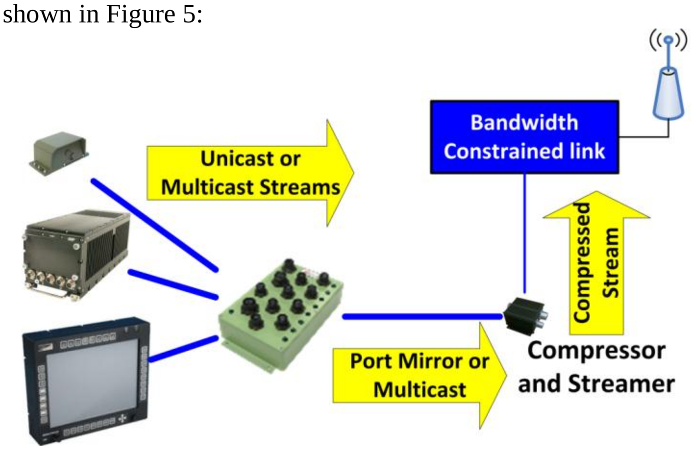

Figure 5: Reference Architecture for Bandwidth Efficiency Applications

Key Elements of this architecture:

- Various streams, unicast or multicast, compressed or uncompressed, are provided from various sources
- Through either multicast or port mirroring, video intended for a bandwidth constrained link is provided to a compressor and streamer device, handling the transcoding to an appropriate datarate for external links (e.g. 64kbps) for live streaming or buffered streaming

This architecture attaches to other architectures as tapped-off video stream.

Archival

The Reference Architecture for Archival applications is shown in Figure 6:

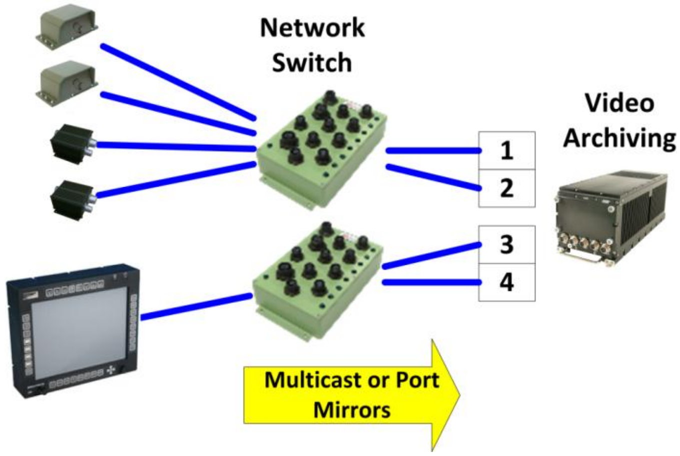

Figure 6: Reference Architecture for Archival Applications

Key Elements of this architecture:

- Various streams, unicast or multicast, compressed or uncompressed, are provided from various sources
- Through either multicast or port mirroring, video intended for archival is delivered to video storage.
- A single archiving video storage device can be connected to multiple networks to increase throughput and flexibility.

Similar to bandwidth efficiency applications, this architecture attaches to other architectures as tapped-off video stream.

Control

The Reference Architecture for Control applications is shown in Figure 7:

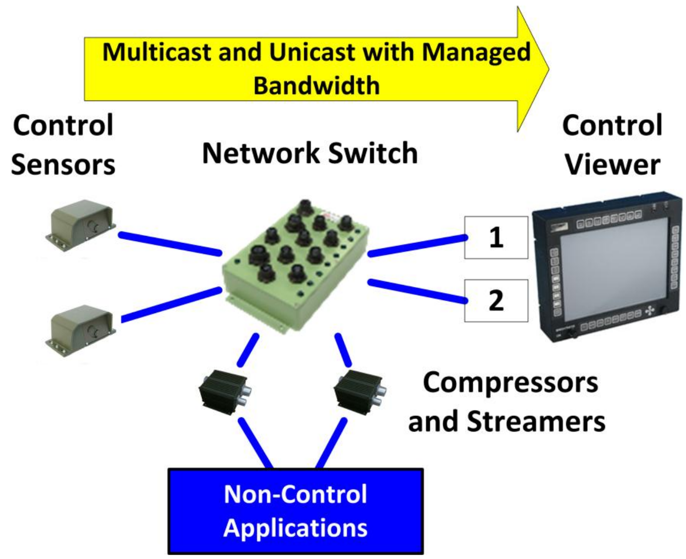

Figure 7: Reference Architecture for Control Applications

Key Elements of this architecture:

- Control Sensors provide low latency streams (e.g. uncompressed or MJPEG2000 compressed) using either multicast or unicast, selected based on quality requirements (SD versus HD)
- In order to clearly constrain network performance, control video streams take advantage of network quality of service mechanisms to guarantee timely delivery.
- Control Viewing device receives low latency control video
- Re-use of control video is provided via multi-cast or port mirroring
- If required, transcoding by compressor / streamer is performed for other video applications (e.g. awareness)
- Assuming frame-based latency calculations, the use of JPEG2000 results in best possible <3 frame period latency (e.g. <100ms at 30fps or <50ms at 60fps).
- If encode, decode, and network transmission latencies are assumed to be <10ms in total, maximum latencies are 2 frame periods + 10ms (e.g. 77ms at 30fps, 43ms at 60fps).
- If display latency is allowed to drop to pixel latency through the use of single buffered video, then the overall latency drops to an average of 1 frame period (for sensor) plus ½ frame period average for display + additional latencies for encode / decode / network transmission. Using the same assumptions as above, this results in ~60ms at 30fps and ~35ms at 60fps.

- Proper frame synchronization of sensor to display can drive the average wait time for pixel updates to a lower and deterministic value.
- Driving frame rates are generally considered under 80ms, or under 50ms, depending on vehicle speeds. Although 60 fps easily meets this, 30 fps generally requires more sophisticated frame synchronization and single buffering to meet the 50ms requirement.

With Gigabit Ethernet, this architecture can easily integrate up to 8 HD low latency visually lossless compressed streams per Gigabit Ethernet Link as shown in Table 1.

ANALYSIS VERSUS VICTORY AND 1GbE INFRASTRUCTURE

The above architectures correlate with the VICTORY Architecture (1.2) in the following ways:

- VICTORY specifies Standard Definition compression formats, specifically MPEG-2 and MPEG-4
- VICTORY recommends network infrastructures of 1Gbps for Switches
- VICTORY specifies support for multicast
- VICTORY specifies support for Quality of Service

VICTORY does not, however, specify the following:

- High Definition compression formats
- Motion JPEG2000 as a compression format, either SD or HD
- Ethernet Switch Port Mirroring

Nothing in the various video distribution architectures contradicts VICTORY Specifications, nor are any required elements a proprietary standard. It is recommended that the missing items be added to the VICTORY Specification given the potential applications.

CONCLUSIONS

Video Distribution with Low Latency and Open Standards is achievable, including drivable video at 30fps with high definition video utilizing Motion JPEG2000. Separated or proprietary video buses specifically for these applications are not absolutely required, and can be accommodated by the VICTORY databus.

Proper system design based using design reference architectures and open standards allows system designers to maintain an open standard approach to video distribution, with the potential to utilize COTS based hardware and software video distribution elements, ensuring interoperability, longevity, and low risk for the vehicle's video distribution implementation.

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