STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

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7. AUTHOR Travis B. Swanston, Kin S. Yen, and Ty A. Lasky		8. PERFORMING ORGANIZATION REPORT NO. UCD-ARR-23-06-30-03
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16. ABSTRACT

The California Department of Transportation (Caltrans) has and is currently installing Intelligent Transportation System (ITS) CCTV sites in multiple areas around the state. Unfortunately, not all manufacturer specifications measure attributes using the same methodologies. In addition, many manufacturers now produce products that provide high throughput but cannot stream video at the ultra-low-speed throughputs needed at remote sites in rural areas of the state. In rural districts, many CCTV sites' communication options are limited to plain old telephone service (POTS) for data transport data, often at 10 kbps or less. Caltrans needed equipment evaluation research under Caltrans rural operating conditions and environments to determine if CCTV video encoders would meet Caltrans performance measures. This research determined how video encoder equipment performs under real-world Caltrans rural operating conditions. The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center determined and evaluated which next-generation video encoder equipment would be viable as Caltrans ITS assets. This report summarizes the results presented in prior project interim reports and provides the final research findings and recommendations.

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Advanced Highway Maintenance and Construction Technology Research Center

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University of California at Davis

Evaluation of Next-Generation CCTV Encoder for ITS Field Elements

Travis B. Swanston, Kin S. Yen &
Ty A. Lasky: Principal Investigator

Report Number: CA23-3873
AHMCT Research Report: UCD-ARR-23-06-30-03
Final Report of Contract: 65A0749 Task 3873

June 30, 2023

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

Problem, Need, and Purpose of Research

The California Department of Transportation (Caltrans) has and is currently installing Intelligent Transportation System (ITS) closed-circuit TV (CCTV) sites throughout the state. New methods of transmitting video from field sites to the Transportation Management Center are being developed to improve video stream quality significantly. Multiple manufacturers produce these "next-generation" encoders and provide Caltrans engineers with specifications and marketing materials. Manufacturer specifications measure attributes using different methodologies, and some products do not meet advertised specifications. In addition, many manufacturers produce products that provide high throughput but cannot stream video at the ultra-low-speed needed at remote sites in rural areas.

In rural districts, many CCTV sites' communication options are limited to plain old telephone service (POTS) for data transport, often at 10 kbps or less. As the video industry pushes the limits of higher bandwidth and increased compression, Caltrans must monitor whether the next-generation video encoders will be able to function in low-bandwidth conditions.

Caltrans needed equipment evaluation research under Caltrans rural operating conditions and environments to determine if CCTV video encoders would meet Caltrans performance measures [1].

The Advanced Highway Maintenance and Construction Technology Research Center determined and evaluated which next-generation video encoder equipment would be viable as rural ITS field equipment options as Caltrans adds to and refreshes ITS assets.

An evaluation is provided based on performance of the chosen video encoder equipment. Details of this evaluation are documented in detail in an interim report [2], and briefly herein, and have been provided to the members of the Rural Program Steering Committee (PSC) and to districts.

Overview of the Work and Methodology

The research involved the following tasks:

1. Project management
2. Assess current Caltrans rural operating conditions and gaps
3. Select and procure hardware

4. Bench testing at AHMCT
5. Final report

The original proposed research included rural field testing of the systems after completion of the bench testing. In addition, the researchers identified additional camera(s) for bench testing. Due to delays from the COVID-19 pandemic, which was in full force through much of this research, the bench testing took longer than anticipated. At the completion of this task, there was insufficient time for meaningful rural field testing by Caltrans personnel, and insufficient time for them to prepare for the testing. Upon conferring with the project manager, it was decided to omit the rural field testing. Several camera systems were procured to support testing of additional models, and some of these were tested. Procurement time for some of the cameras was longer than ordinary, so these systems were not tested. One vendor indicated a six-month time of arrival, which would have allowed for testing. However, this camera did not arrive after nine months due to COVID19-related supply chain issues, and AHMCT canceled this order to avoid billing beyond the contract period.

Major Results and Recommendations

Quantitative data from controlled testing of the CCTV encoder systems (research Task 4) is a key deliverable. These data are presented in detail in the interim report [2] included in Appendix C. Qualitative findings from preparing for and executing the CCTV encoder tests may be more useful to Caltrans in the long-term. For example, cameras from some vendors are excellent at high-speed streaming in urban areas but cannot stream at sufficiently low rates for rural installations. These findings are detailed in Chapter 3 as well as Appendix C.

To facilitate the multiple camera and multiple vendor testing of this research effort, custom CCTV camera configuration code was developed. This code was not an originally listed as a deliverable. However, AHMCT is making this code available to Caltrans as part of this research project, and we believe this tool will provide substantial long-term value to Caltrans Traffic Operations and the TMC.

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Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
BNC	Bayonet Neill-Concelman
Caltrans	California Department of Transportation
CCTV	Closed-Circuit TV
CWWP	Commercial Wholesale Web Portal
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
HDS	High-Definition-System
HTTP	Hypertext Transfer Protocol
ITS	Intelligent Transportation System
LTE	Long-Term Evolution
M-JPEG	Motion-JPEG
PM	Project Manager
POTS	Plain Old Telephone Service
PSC	Program Steering Committee
RTMP	Real-Time Messaging Protocol
RTSP	Real Time Streaming Protocol
SFTP	Secure FTP
SSH	Secure Shell

Acronym	Definition
TMC	Transportation Management Center

Acknowledgments

The authors thank the California Department of Transportation (Caltrans) for their support, in particular Jeremiah Pearce and Keith Koeppen with District 2, Andres Chavez and Dean Campbell with District 3, Sam Campos with District 6, Dirk Spaulding with District 8, with Dung Le District 10, John Castro with Headquarters Traffic Engineering, and Sean Campbell with the Division of Research, Innovation and System Information. The authors acknowledge the dedicated efforts of the AHMCT team who have made this work possible.

Chapter 1: Introduction

Problem

The California Department of Transportation (DOT) (Caltrans) has and is currently installing Intelligent Transportation System (ITS) closed-circuit TV (CCTV) sites in multiple areas around the state. New methods and efficiencies of transmitting video from the field sites to the Transportation Management Center (TMC) are being developed to improve the quality of the video stream significantly. Multiple manufacturers produce these “next-generation” encoders and provide Caltrans engineers with specifications and marketing materials. Unfortunately, not all manufacturer specifications measure attributes using the same methodologies, and some products do not meet their advertised manufacturer specifications. In addition, many manufacturers now produce products that provide high throughput but cannot stream video at the ultra-low-speed throughputs needed at remote sites in rural areas of the state.

In rural districts, many CCTV sites’ communication options are limited to plain old telephone service (POTS) for data transport, often at 10 kbps or less. As the video industry pushes the limits of higher bandwidth and increased compression, Caltrans must monitor whether the next-generation video encoders will be able to function in low-bandwidth conditions.

Caltrans needed equipment evaluation research under Caltrans rural operating conditions to determine if CCTV video encoders would meet Caltrans performance measures.

Objectives

Several companies have next-generation video encoder equipment. Each company has a specification sheet that is often difficult to compare with their competitors. The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center determined and evaluated which next-generation video encoder equipment would be viable as rural ITS field equipment options as Caltrans adds to and refreshes ITS assets.

One of the primary goals of this research was to characterize how the selected encoding devices can perform under a variety of network conditions, especially under the low-bitrate, high-error conditions that are common at rural field element sites. A secondary goal was to review other relevant features of the devices that make impact its applicability to different types of sites. The purpose of these goals is to facilitate future device selection for various sites, given their particular network conditions and other attributes.

An evaluation is provided based on performance of the chosen video encoder equipment. Details of this evaluation are documented herein and have been provided to the members of the Rural Program Steering Committee (PSC) and to districts.

How well a video stream performs under different network conditions is primarily a function of the configurability and feature set of the encoding device. A poor choice of decoder on the stream-consuming end can also affect the stream quality of course. However the streaming protocols supported by the devices under consideration do not dynamically adapt to feedback from the decoder so, as long as the decoder is stable and fully supports the encoding mode being used, its impact on stream quality should be minimal.

Characterizing how the video streams from a given encoding device may perform under various network conditions involves carefully considering the device's range of features and relevant configuration parameters. First, we will explore these features and parameters for each selected device, examine how varying network conditions may affect the resulting stream, and present qualitative and quantitative data collected during testing in order to facilitate optimal device configuration for sites of various types. Second, we will draw comparisons between devices and their range of encoding modes and parameters and other features in order to facilitate optimal device selection for sites of various types.

Scope

This report summarizes the results presented in prior interim project reports, which are also included in the appendices, and provides the final research findings, including final recommendations from the research.

Overview of Research Results and Benefits

The key deliverables of this project include:

- Interim report summarizing Caltrans operating conditions and usage for CCTV encoders (Appendix B) [1]
- Interim report summarizing controlled testing of CCTV encoder systems (Appendix C) [2]
- Procured hardware
- Custom CCTV configuration software (added deliverable)
- Final report

External Impacts on Research

The original proposed research included rural field testing of the systems after completion of the bench testing. In addition, the researchers identified additional camera(s) for bench testing. Due to delays from the COVID-19 pandemic, which was in full force through much of this research, the bench testing took longer than anticipated. At the completion of this task, there was insufficient time for meaningful rural field testing by Caltrans personnel, and insufficient time for them to prepare for the testing. Upon conferring with the project manager, it was decided to omit the rural field testing. Several camera systems were procured to support testing of additional models, and some of these were tested. Procurement time for some of the cameras was longer than ordinary, so these systems were not tested. One vendor indicated a six-month time of arrival, which would have allowed for testing. However, this camera did not arrive after nine months due to COVID19-related supply chain issues, and AHMCT canceled this order to avoid billing beyond the contract period.

Chapter 2: Summary of Prior Interim Reports

Project deliverables included two previously completed interim reports, which are summarized briefly in this chapter. For details, the reader is referred to the original reports in standalone form or in the appendices.

Evaluation of Next-Generation CCTV Encoder for ITS Field Elements - Caltrans Operating Conditions and Usage for CCTV Encoders [1]

As part of the kickoff meeting and subsequent discussions, based on Project Panel inputs and direction, AHMCT ascertained Caltrans rural operating conditions and identified gaps related to CCTV encoder systems, including field conditions as well as characteristics of rural communications channels for the resulting images. AHMCT identified known gaps related to Caltrans use of CCTV encoders in rural environments as well as the categories of CCTV encoder systems to be evaluated in the following research tasks. Where feasible, the report identified specific CCTV encoder systems to evaluate in a prioritized list.

To accomplish the objectives of this task of the study, AHMCT held discussions with the Project Panel and the Project Manager, and a survey was created and provided to five Caltrans districts (District 2 [D2], D3, D6, D8, and D10). The data gathered from these discussions and the survey were aggregated and analyzed.

The data gathered included information on current and desired video encoding standards, streaming protocols, characteristics of field element data connections, expected ambient temperature ranges at CCTV field element sites, and other functional requirements, such as device management interfaces, extra features, etc. Information on next-generation CCTV camera and encoder equipment that Caltrans engineers were currently considering for potential future use was also gathered.

Evaluation of Next-Generation CCTV Encoder for ITS Field Elements - Controlled Testing of CCTV Encoder Systems [2]

AHMCT performed controlled testing of the CCTV encoder systems. Testing within this task validated the CCTV encoder systems against vendor-neutral specifications and requirements developed jointly between AHMCT and the Project Panel. This testing included intra-camera evaluations and comparisons for varying configurations and settings, as well as inter-camera comparisons of comparable configurations for the cameras included in the tests. The four cameras included are shown in Figure 2.1 through Figure 2.4. Table 21 provides the list of devices tested.

Table 2.1: Devices selected for testing

Device	Type	Part #	Firmware Version
Axis Q8752-E	CCTV camera with integrated encoder	01838-001	10.12.153
Bosch MIC inteox7100i	CCTV camera with integrated encoder	MIC-7602-Z30GR	8.46.0030
CostarHD RISE4260HD	CCTV camera with integrated encoder	4261-1000	Core 4.1.92, Rise 4.1.323
WTI Viper/SidewinderHD	CCTV camera with integrated encoder	VS720-H.264-HD30L-POE-R	2.15.0.r

Figure 2.1: Axis Q8752-E bispectral camera

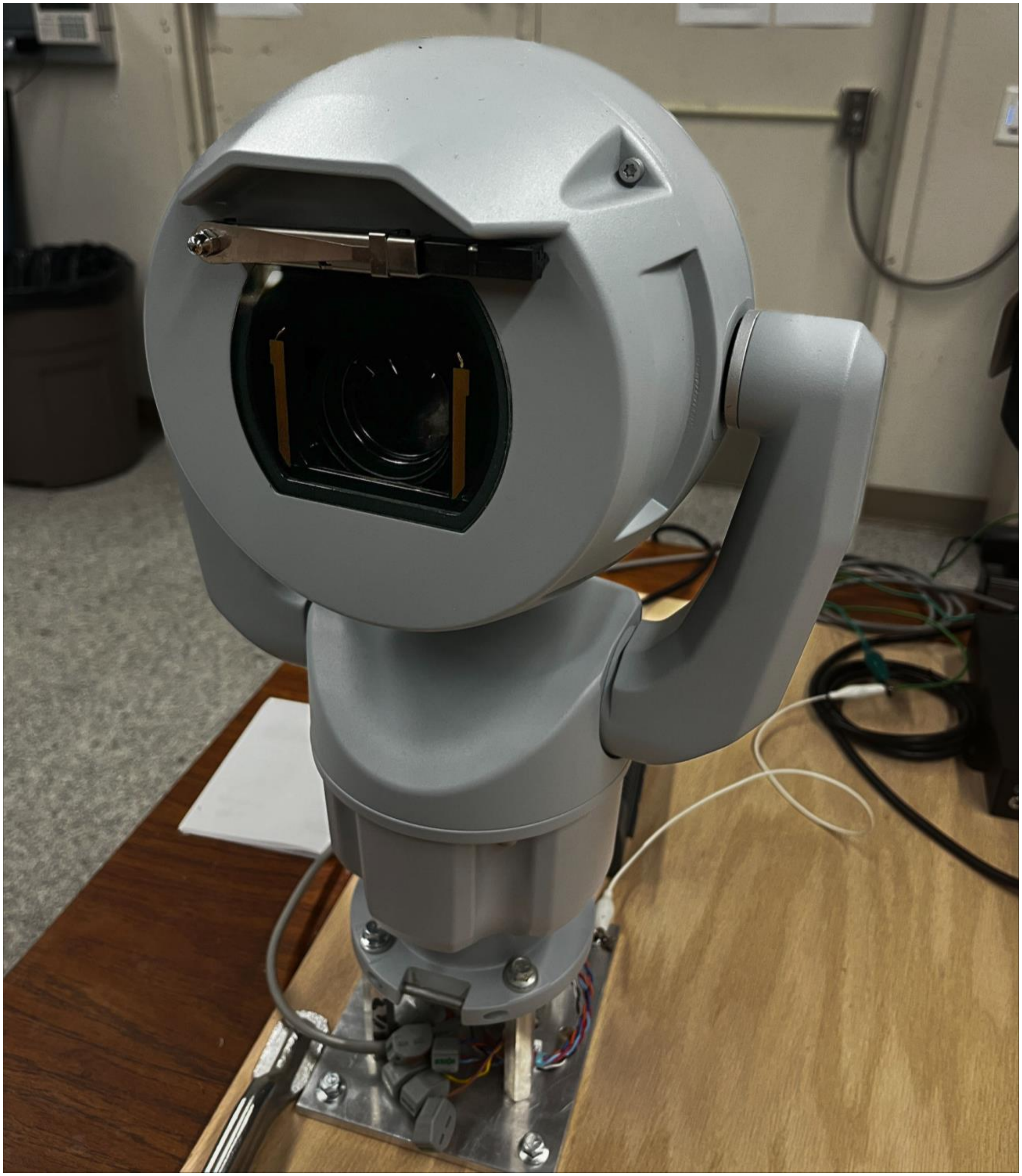

Figure 2.2: Bosch MIC inteox 7100i camera

Figure 2.3: CostarHD RISE 4260HD camera

Figure 2.4: WTI Viper/Sidewinder HD camera

Two types of testing were performed in this study: video stream testing, and static image testing. While the aim of this research primarily relates to video streaming, each Caltrans district makes extensive use of static images, acquired by means of periodic fetches from CCTV encoders at field element sites via the Caltrans CCTV Information Relay located in each district. For many rural CCTV sites which do not have the network capacity to support a useable video stream, generating and transferring these static images is the principal mode of use. Typically, these images are encoded in JPEG format and fetched from the encoder using HTTP or Hypertext Transfer Protocol Secure (HTTPS). Since this remains an important use case for highway surveillance CCTV encoders, static image testing was included in this research.

The testing was carried out in an AHMCT laboratory. A 4K display was placed on a table at one end of the room, and the CCTV devices were arranged on another table at a sufficient distance from the display to allow for clear focus on the image shown on the display. This configuration is illustrated in Figure 2.5 through Figure 2.7, and is discussed in detail in Appendix C.

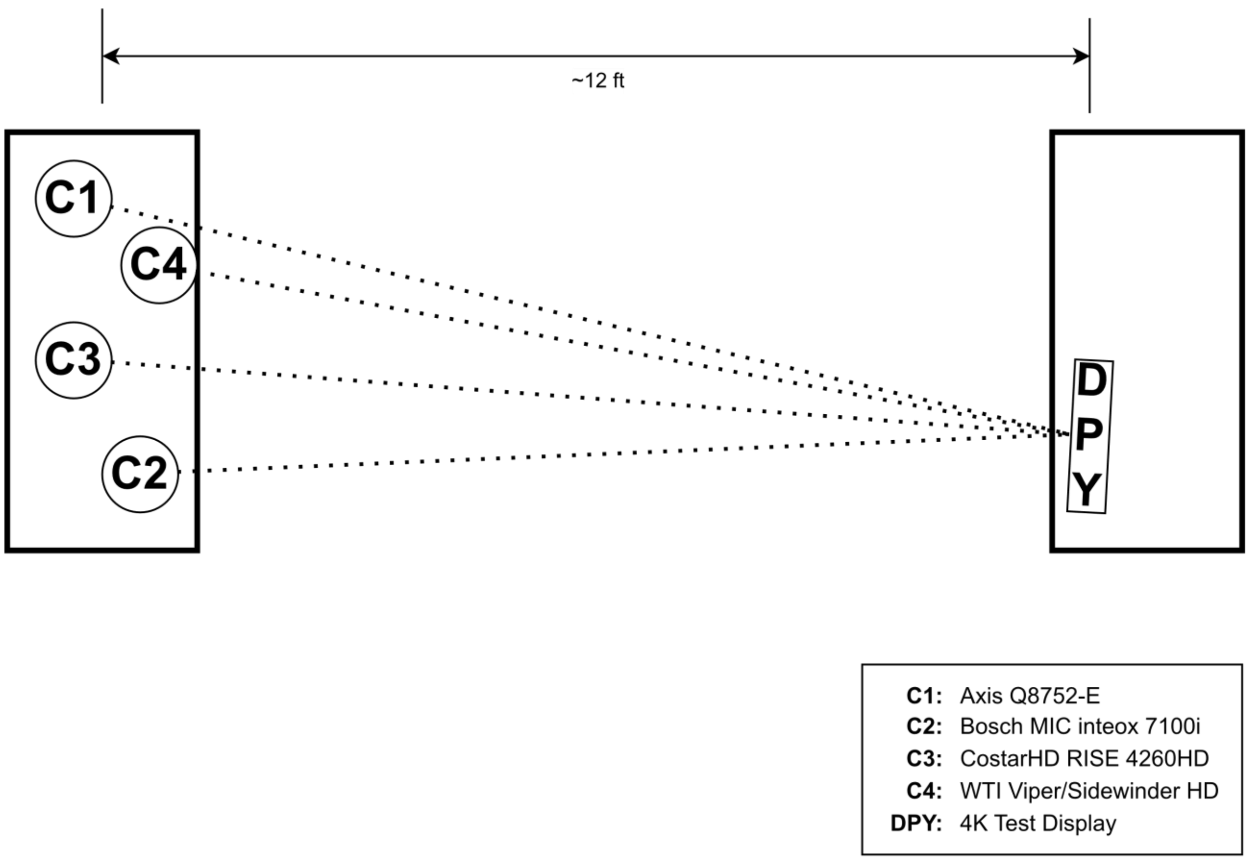

Figure 2.5: Test setup

Figure 2.6: CCTV devices mounted for testing

Figure 2.7: CCTV devices aimed at the test display

The primary goals of the data analysis phase were to determine, for each device:

- How do the various stream configurations tested compare with each other, especially in terms of bitrate and frame loss estimates?
- How well does the device tend to keep the stream bitrate within range of the specified target and/or maximum bitrate parameters?
- How do network bandwidth limitations affect the stream as received by the client/decoder?

Chapter 3:
Conclusions and Future Research

Key contributions of this research project included:

- Performance of various CCTV systems and configurations vs. typical rural operating needs
- Performance comparison across CCTV cameras for comparable configurations
- Custom CCTV configuration software
- A test methodology which can support future device testing, evaluation, and comparison
- Device-specific conclusions based on controlled bench testing
- Novel visualization tools and methodologies for assessing CCTV system performance, including the stream quality analysis chart
- Numerous test result tables and charts for various configurations for the four tested devices.

The purpose of these tables is to aid in the stream configuration process and can help answer two key questions:

1. For a given resolution and frame rate, what are reasonable minimum values for target rate (if applicable) and maximum rate that will produce a reliable stream with this encoding?
2. For a communications link with a given nominal bitrate, what is the highest resolution and/or frame rate that can be streamed reliably with this encoding?

These tables help find approximate answers to these questions. Once that is done, the operator can use these answers as a starting point in tuning the stream until the visual quality is acceptable.

COVID19-Related Delays and Impacts

The proposed research included rural field testing of the systems after completion of the bench testing. In addition, the researchers identified additional camera(s) for bench testing. Due to delays from the COVID-19 pandemic, which was in full force through much of this research, the bench testing took longer than anticipated. At the completion of that task, there was insufficient time for meaningful rural field testing by Caltrans personnel and insufficient time for them to prepare for the testing. Upon conferring with the project manager, it was decided to omit the rural field testing. Several camera systems were procured to support testing of additional models, and some of these cameras were tested. Procurement time for some of the cameras was longer than ordinary, so these systems were not tested. One vendor indicated a six-month time of arrival, which would have allowed for testing. However, this camera did not arrive after nine months due to COVID19-related supply chain issues, and AHMCT canceled this order to avoid billing beyond the contract period.

Future Research

Future evaluation should include completing the field installation, testing, and associated evaluation. However, due to the pace of technological change in this area, this is problematic, in that by the time additional research is conducted to address field testing, this report's findings will be obsolete.

Future research and deployment should leverage the software tools and more importantly the methodology developed herein to carefully test, evaluate, and compare emerging devices. The tools should also be used to answer the key encoding questions:

1. For a given resolution and frame rate, what are reasonable minimum values for target rate and maximum rate that will produce a reliable stream with this encoding?
2. For a communications link with a given nominal bitrate, what is the highest resolution and/or frame rate that can be streamed reliably with this encoding?

Following this, the user can fine-tune the configuration for best results.

References

[1] T. B. Swanston, K. S. Yen, and T. A. Lasky, "Evaluation of Next-Generation CCTV Encoder for ITS Field Elements - Caltrans operating conditions and usage for CCTV encoders," AHMCT Research Center, Interim Report UCD-ARR-21-06-30-02, Jun. 2021.
[2] T. B. Swanston, K. S. Yen, and T. A. Lasky, "Evaluation of Next-Generation CCTV Encoder for ITS Field Elements - Controlled testing of CCTV encoder systems," AHMCT Research Center, Interim Report UCD-ARR-23-03-31-02, Jun. 2023.

Appendix A:
CCTV Operating Conditions and Characteristics

Based on initial discussions with the project manager and project champion, the following CCTV operating conditions and characteristics have been identified as of interest in this study:

- Testbeds
  - Existing
  - Need to construct
- District type
  - Rural
- Bandwidth
  - Ultra-low (up to 10 kbps)
  - Low (10 kbps – 128 kbps)
  - Medium (128 kbps – 1.5 Mbps) , if available
  - High (greater than 1.5 Mbps), if available
- JPEG needs for CWWP2
- H.264 needs for streaming / Wowza
  - RTMP
  - RTSP
  - HDS
  - MJPEG
- Decoding digital video at the district office
- Environments
  - Coastal
  - Mountain
  - Desert
  - Metropolitan, if available
- Operating temperature range
- Form factor
  - Integrated CCTV
    - Dome
    - Pole-mounted 360 deg PTZ
  - Stand-alone enclosure
    - Rack-mountable
    - Din-rail
- Cabling and physical interface
  - Analog
    - BNC (video)
    - Serial (RS-422)
  - Digital
    - Ethernet
- Interfaces
  - HTTP
  - SSH
  - SFTP
  - Others
- Scene lighting - function of CCTV unit
  - Luminaire
  - Moonlight
  - Headlights
  - Integration

Appendix B: Interim Report: Caltrans Operating Conditions and Usage for CCTV Encoders

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16. ABSTRACT

The California Department of Transportation (Caltrans) has and is currently installing Intelligent Transportation System (ITS) CCTV sites in multiple areas around the state. Unfortunately, not all manufacturer specifications measure attributes using the same methodologies. In addition, many manufacturers now produce products that provide high throughput but cannot stream video at the ultra-low-speed throughputs needed at remote sites in the rural areas of the state. In rural districts, many CCTV sites have communication options limited to plain old telephone service (POTS) to transport data, often at 10 kbps or less. Caltrans needed equipment evaluation research under Caltrans rural operating conditions and environments to determine if CCTV video encoders would meet Caltrans performance measures. This research is determining how video encoder equipment performs under real-world Caltrans rural operating conditions. The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center will determine and evaluate which next-generation video encoder equipment would be viable as Caltrans ITS assets. This report summarizes the results for Caltrans operating conditions and usage for CCTV encoders.

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
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Evaluation of Next-Generation CCTV Encoder for ITS Field Elements - Caltrans Operating Conditions and Usage for CCTV Encoders

Travis B. Swanston, Kin S. Yen &
Ty A. Lasky: Principal Investigator

Report Number: CA22-3873
AHMCT Research Report: UCD-ARR-21-06-30-02
Final Report of Contract: 65A0749 Task 3873

November 17, 2021

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

To ascertain the current operating conditions, needs, and limitations of existing Caltrans CCTV camera and encoder systems, a survey was provided to five districts (District 2 [D2], D3, D6, D8, and D10). Information collected by this survey included expected minimum and maximum ambient temperatures, types of network connections used for CCTV field elements, desired support for video streaming protocols, and other data interfacing requirements. In addition, the survey collected information on CCTV camera and encoder equipment that each district is considering as candidates for potential future deployment.

Problem, Need, and Purpose of Research

A thorough understanding of the environmental and functional needs of each district with respect to CCTV cameras and encoders was needed in order to determine a set of equipment options to be evaluated in this study as well as to determine the specific operational conditions (e.g. temperature ranges, network conditions) against which candidate equipment will be tested.

Background

Reliable and well-functioning CCTV sites are critical to Caltrans operations. The environmental and functionality claims of CCTV equipment manufacturers cannot always be taken at face value due to differing methodologies used for measuring or testing. In addition, many manufacturers now produce products that provide high-quality, data-efficient video streams, yet still fail to reliably function across the types of low-bandwidth, high-latency connections used by many rural sites (often 10 kbps or less). The testing to be performed in this study will seek to validate and quantify the important operational characteristics and functionality of a set of candidate CCTV equipment.

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List of Tables

List of Acronyms and Abbreviations

Acronym	Definition
3G	Third-generation wireless mobile telecommunications technology
4G	Fourth-generation wireless mobile telecommunications technology
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
ASE	AT&T Switched Ethernet
ATMS	Advanced Traffic Management System
BNC	Bayonet Neill–Concelman
Caltrans	California Department of Transportation
CCTV	Closed-Circuit TV
COTS	Commercial Off–The-Shelf
CWWP2	Commercial Wholesale Web Portal 2
DIN	Deutsches Institut für Normung
DOT	Department of Transportation
DRISI	Division of Research, Innovation and System Information
DSL	Digital Subscriber Line
FTP	File Transfer Protocol
GHCN	Global Historical Climatology Network
HDR	High Dynamic Range
HDS	HTTP Dynamic Streaming

Acronym	Definition
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
IP	Ingress Protection
IRIS	Intelligent Roadway Information System
ISDN	Integrated Services Digital Network
ITS	Intelligent Transportation Systems
JPEG	Joint Photographic Experts Group
LTE	Long-Term Evolution
MJPEG	Motion-JPEG
NOAA	National Oceanic and Atmospheric Administration
nSSP	Non-Standard Special Provision
NTP	Network Time Protocol
NWS	National Weather Service
ONVIF	Open Network Video Interface Forum
POTS	Plain Old Telephone Service
PSC	Program Steering Committee
PTZ	Pan-Tilt-Zoom
RS-232	Recommended Standard 232
RS-422	Recommended Standard 422
RTMP	Real-Time Messaging Protocol
RTP	Real-time Transport Protocol
RTSP	Real Time Streaming Protocol

Acronym	Definition
SFTP	SSH File Transfer Protocol
SNMP	Simple Network Management Protocol
SR	State Route
SSH	Secure Shell
TCP	Transmission Control Protocol
TMC	Transportation Management Center
UDP	User Datagram Protocol

Acknowledgments

The authors thank the California Department of Transportation (Caltrans) for their support, particularly Jeremiah Pearce and Keith Koeppen with District 2; Dean Campbell and Andres Chavez with District 3; Dirk Spaulding with District 8; Dave Le with District 10; and Sean Campbell with the Division of Research, Innovation and System Information. The authors acknowledge the dedicated efforts of the AHMCT team who have made this work possible.

Chapter 1: Introduction

Problem

The California Department of Transportation (DOT) (Caltrans) has and is currently installing Intelligent Transportation Systems (ITS) Closed-Circuit TV (CCTV) sites in multiple areas around the state. New methods and efficiencies of transmitting video from the field sites to the Transportation Management Center (TMC) are being developed, which is significantly improving the quality of the video stream. Multiple manufacturers produce these "next-generation" encoders and provide Caltrans engineers with specifications and marketing materials. Unfortunately, not all manufacturer specifications measure attributes using the same methodologies, and products sometimes do not meet their advertised specifications, making it difficult to objectively compare these products. In addition, many manufacturers now produce products that provide high-quality, data-efficient video streams, yet still fail to reliably function across the types of low-bandwidth, high-latency connections used by many sites in the rural areas of the state.

Objectives

This study seeks to evaluate a set of next-generation CCTV encoders and evaluate the extent to which each is able to function across the spectrum of real-world operating conditions (in particular environment and connectivity) that represent Caltrans CCTV sites. It is expected that these results will be valuable in determining which next-generation CCTV encoder equipment will be a viable option, especially for rural sites, as Caltrans adds to and refreshes its assets.

As a first step in this study, AHMCT ascertained the current operating conditions, functional needs, and limitations of existing Caltrans CCTV camera and encoder systems. In addition, we sought to learn which next-generation CCTV camera and encoder equipment Caltrans engineers were currently considering for potential future use.

Scope

To accomplish the objectives of this task of the study, AHMCT held discussions with the Project Panel and the Project Manager, and a survey was created and provided to five Caltrans districts (District 2 [D2], D3, D6, D8, and D10). The data gathered from these discussions and the survey were aggregated and analyzed.

The data gathered included information on current and desired video encoding standards, streaming protocols, characteristics of field element data connections, expected ambient temperature ranges at CCTV field element sites, and other functional requirements, such as device management interfaces, extra features, etc. Information on next-generation CCTV camera and encoder equipment that Caltrans engineers were currently considering for potential future use was also gathered.

Chapter 2: Caltrans Rural CCTV Operating Conditions and Gaps

Current Operating Conditions and Usage

Field Element Network Connections

Table 1 summarizes the survey data collected on district CCTV field element network connections. Some data has been grouped into broader classes (DSL subtypes, LTE and 4G, etc.)

Table 1: Survey data collected on district CCTV field element network connections (see acronym table for definitions)

	D2	D3	D6	D8	D10
fiber	•	•	•	•	•
wireless/μwave	•	•		•	
4G/LTE	•		•	•	•
DSL		•		•	•
3G					
cellular[1]					
cable		•			
ISDN	•				
POTS	•				
ASE		•			

[1] The specific classes of cellular service (e.g., 3G, LTE, 4G) utilized by D3 are yet to be determined.

Encoding Standards and Streaming Protocols

Table 2 summarizes the survey data collected on district video encoding standards and streaming protocols.

Table 2: Survey data collected on district video encoding standards and streaming protocols (see acronym table for definitions)

	D2	D3	D6	D8	D10
H.264 via RTSP/RTP	●	●	●	●	●
H.265 via RTSP/RTP			●		●
MJPEG via HTTP(S)	●		●	●	●

In the case of RTSP/RTP, support for UDP, TCP, and HTTP is specified in Caltrans' Non-Standard Special Provisions (nSSPs).

Other Functional Requirements and Desired Capabilities

Table 3 summarizes the survey data collected from districts on other functional requirements and desired capabilities for CCTV camera/encoder systems.

Table 3: Survey data collected from districts on other functional requirements and desired capabilities for CCTV camera/encoder systems (see acronym table for definitions)

	D2	D3	D6	D8	D10
HTTP/HTTPS	●	●	●	●	●
SSH	●	●	●		
ONVIF	●	●		●	●
SNMP	●	●		●	
FTP				●	
lens snow/ice removal		●			
NTP		●		●	

	D2	D3	D6	D8	D10
onboard scheduler		●			
RS-232/422	●				
SFTP	●				
SMTP				●	
IGMP				●	
wide dynamic range		●		●	

Expected Temperature Ranges

Table 4 presents the survey data collected from districts on expected temperature ranges. The responses likely include a mixture of ambient temperature ranges (for integrated CCTV units) and cabinet temperature ranges (for encoders).

Table 4: Survey data collected on district ambient temperature ranges

	Min. °F	Max. °F
D2	-40	125
D3	-25	130
D6	32	106
D8	10	120
D10	35	112
extremes	-40	130

Historical Ambient Temperature Ranges

To better understand the ambient temperature extremes likely to be encountered in each district, data from the Global Historical Climatology

Network (GHCN) database[2] was analyzed. The GHCN includes data from a large collection of land surface weather stations that has been subjected to a suite of quality assurance reviews. The GHCN dataset for California goes back more than a century and is hosted by the National Weather Service (NWS) National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center.[3] The time range covered by data from each particular station varies, although most ranges span decades.

Table 5 presents the results of our processing of GHCN data to generate a reasonable estimate of historical ambient temperature extremes encountered in each Caltrans district.

Table 5: Estimated historical ambient temperature extremes by district

	Min. °F	Max. °F
D1	-9	119
D2	*-36*	*121*
D3	*-45*	*123*
D4	7	117
D5	0	121
D6	*-32*	*124*
D7	-9	129
D8	*-25*	*127*
D9	-37	134
D10	*-45*	*119*
D11	-1	129
D12	16	116

[2] Menne, M.J., I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, S. Anthony, R. Ray, R.S. Vose, B.E. Gleason, and T.G. Houston, 2012: Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.26

[3] NOAA National Climatic Data Center (http://doi.org/10.7289/V5D21VHZ) (accessed 9 Jun. 2021)

	Min. °F	Max. °F
extremes	-45	134
Extremes in D2, D3, D6, D8, and D10	*-45*	*127*

Current Gaps and Limitations

Streaming

Obtaining a reliable and quality video stream from a field site can be a challenge in rural areas due to limited network connectivity options. This situation may be improved through the use of more modern encoding standards. Earlier devices supported encodings such as MJPEG and MPEG-4. While these encodings work well over network connections with sufficient bandwidth, it is difficult to use them reliably over many of the types of connections available in rural sites. Newer CCTV and encoder devices support encodings, such as H.264 and H.265, that are able to deliver more bandwidth-efficient video streams. Support for more efficient encoding standards is a desirable feature for any new integrated CCTV or encoder device intended for rural use.

Device Management and Control

Configuring and controlling earlier CCTV devices generally required the use of manufacturer-specific protocols. This resulted in additional complexity for software used to manage these devices. There is currently an industry trend to unify support for a common CCTV interface standard called Open Network Video Interface Forum (ONVIF). Given the current momentum toward supporting ONVIF, it is a desirable feature for new CCTV devices.

Dynamic Range

It is common in rural areas for CCTVs to be positioned in such a way that much of their field of view consists of very dark areas. When the CCTV captures high-brightness areas, (such as street lights or vehicle headlights) the resulting image will wash out the bright spots resulting in low quality images. Devices that support high dynamic range[4] (HDR) are likely to produce a more useful image under these circumstances.

[4] The precise meaning of the term "high dynamic range" varies among manufacturers, but the general idea tends to be the same.

In the survey, one district expressed a desire for CCTVs with HDR, and AHMCT has previously encountered CCTV sites in other districts that would also likely benefit from HDR support.

Environmental

One of the goals of this research project is to establish, through testing, a reasonable level of confidence that a select group of devices is able to operate at the temperature and humidity extremes likely to be encountered at Caltrans field element sites. In addition, manufacturer-supplied ingress protection (IP) ratings and snow/ice mitigation features will be considered during the device selection and noted in the review process.

Equipment of Interest

Table 6: Equipment of interest

Make	Model	Type	Interested District(s)	Available for Loan?	Notes
Axis	P56 series	integrated	8	maybe	lower power/PTZ
Axis	Q6055-E / Q6075-E	integrated	10	no	available for field test
Axis	Q6215-E	integrated	8	maybe	high power/PTZ
Axis	Q6155-E	integrated	8	unknown	220° vert. tilt
Axis	Q7411	encoder	6	yes	
Axis	Q7424-R Mk II	encoder	2	yes	
Axis	Q8685-E	integrated	2	unknown	
Axis	Q8752-E	integrated	2	no	
CostarHD	RISE 4260HD (4261)	integrated	6, 10	no	may be available for remote testing
CostarHD	RISE 4260HD (4269-1000-02)	integrated	2, 10	yes	

Make	Model	Type	Interested District(s)	Available for Loan?	Notes
WTI	VS720-H.264-HD30L-AC-A	integrated	2, 10	unknown	
WTI	Sidewinder	integrated	6	no	may be available for remote testing
WTI	Sidewinder (SW720AP)	integrated	10	yes	
WTI	Sidewinder (SW720P-H.264-HD)	integrated	3	yes	
WTI	Sidewinder (thermal)	integrated	3	not yet	D3 currently does not have one
Pelco	ES6230	integrated	6	no	may be available for remote testing

Appendix A:
CCTV Operating Conditions and Characteristics

Based on initial discussions with the project manager and project champion, the following CCTV operating conditions and characteristics were identified at the initiation of this study:

- Testbeds
    - Existing
    - Need to construct
- District type
    - Rural
- Bandwidth
    - Ultra-low (up to 10 kbps)
    - Low (10 kbps – 128 kbps)
    - Medium (128 kbps – 1.5 Mbps) , if available
    - High (greater than 1.5 Mbps), if available
- JPEG needs for CWWP2
- H.264 needs for streaming / Wowza
    - RTMP
    - RTSP
    - HDS
    - MJPEG
- Decoding digital video at the district office
- Environments
    - Coastal
    - Mountain
    - Desert
    - Metropolitan, if available
- Operating temperature range
- Form factor
    - Integrated CCTV
        - Dome
        - Pole-mounted 360 degree PTZ
    - Stand-alone enclosure
        - Rack-mountable
        - DIN-rail
- Cabling and physical interface
    - Analog
        - BNC (video)
        - Serial (RS-422)
    - Digital
        - Ethernet
- Interfaces
    - HTTP
    - SSH
    - SFTP
    - Others
- Scene lighting - function of CCTV unit
    - Luminaire
    - Moonlight
    - Headlights
    - Integration

Appendix C:
Interim Report: Controlled Testing of CCTV Encoder Systems

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16. ABSTRACT

The California Department of Transportation (Caltrans) has and is currently installing Intelligent Transportation System (ITS) CCTV sites in multiple areas around the state. Unfortunately, not all manufacturer specifications measure attributes using the same methodologies. In addition, many manufacturers now produce products that provide high throughput but cannot stream video at the ultra-low-speed throughputs needed at remote sites in the rural areas of the state. In rural districts, many CCTV sites have communication options limited to plain old telephone service (POTS) to transport data, often at 10 kbps or less. Caltrans needed equipment evaluation research under Caltrans rural operating conditions and environments to determine if CCTV video encoders would meet Caltrans performance measures. This research determined how video encoder equipment performs under real-world Caltrans rural operating conditions. The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center determined and evaluated which next-generation video encoder equipment would be viable as Caltrans ITS assets. This report summarizes the CCTV encoder controlled testing.

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Advanced Highway Maintenance and Construction Technology Research Center

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Evaluation of Next-Generation CCTV Encoder for ITS Field Elements - Controlled Testing of CCTV Encoder Systems

Travis B. Swanston, Kin S. Yen &
Ty A. Lasky: Principal Investigator

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Acronyms and Abbreviations

Acronym	Definition
2G	Second-Generation (cellular network system)
3G	Third-Generation (cellular network system)
4G	Fourth-Generation (cellular network system)
5G	Fifth-Generation (cellular network system)
ABR	Average Bitrate
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
AVC	Advanced Video Coding
B-frames	Bidirectional predicted frames
BNC	Bayonet Neill-Concelman
BRI	Basic Rate Interface
Caltrans	California Department of Transportation
CBR	Constant Bitrate
CCTV	Closed-Circuit TV
CPU	Central Processing Unit
CWWP	Commercial Wholesale Web Portal
DASH	Dynamic Adaptive Streaming over HTTP
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
DSL	Digital Subscriber Line

Acronym	Definition
FPS	Frames Per Second
FTP	File Transfer Protocol
GOP	Group of Pictures
H.264	ITU-T Recommendation H.264; MPEG-4 Part 10; AVC
H.265	ITU-T Recommendation H.265; MPEG-H Part 2; HEVC
HD	High Definition
HDS	High-Definition-System
HEVC	High Efficiency Video Coding
HLS	HTTP Live Streaming
HTTP	Hypertext Transfer Protocol
HTTPS	HTTP Secure
IBP	I-frame, B-frame, P-frame
IDR	Instantaneous Decoding Refresh
I-frames	Intra-coded frames, a.k.a. key frames
ISDN	Integrated Services Digital Network
ITS	Intelligent Transportation System
ITU	International Telecommunication Union
ITU-T	Telecommunication Standardization Sector of ITU
JPEG	Joint Photographic Experts Group
LTE	Long-Term Evolution
MBR	Maximum Bitrate
M-JPEG	Motion-JPEG

Acronym	**Definition**
MPEG	Moving Picture Experts Group
MPEG-4	MPEG group of standards 4
MPEG-H	MPEG group of standards H
MPEG-TS	MPEG Transport Stream
ONVIF	Open Network Video Interface Forum
P-frames	Predicted frames, a.k.a. delta frames
PM	Project Manager
POTS	Plain Old Telephone Service
PSC	Program Steering Committee
PTZ	Pan-Tilt-Zoom
RTCP	Real-time Transport Control Protocol
RTMP	Real-Time Messaging Protocol
RTP	Real-time Transport Protocol
RTSP	Real Time Streaming Protocol
SD	Secure Digital
SFTP	Secure FTP
SSH	Secure Shell
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
UDP	User Datagram Protocol
UHD	Ultra-High Definition
VBR	Variable Bitrate

Acronym	Definition
WTI	Wireless Technology, Inc.

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Chapter 1: Introduction

Problem

The California Department of Transportation (DOT) (Caltrans) has and is currently installing Intelligent Transportation System (ITS) Closed-Circuit TV (CCTV) sites in multiple areas around the state. New methods and efficiencies of transmitting video from the field sites to the Transportation Management Center are being developed, significantly improving the quality of the video stream. Multiple manufacturers produce these "next-generation" encoders and provide Caltrans engineers with specifications and marketing materials. Unfortunately, not all manufacturer specifications measure attributes using the same methodologies and some products do not meet their advertised manufacturer specifications. In addition, many manufacturers now produce products that provide high throughput but cannot stream video at the ultra-low-speed throughputs needed at remote sites in the rural areas of the state. Caltrans understands the operating environments of the equipment it deploys. Testing equipment in a lab on a benchtop differs significantly from testing equipment in actual real-world operating conditions.

In rural districts, many CCTV sites have communication options limited to plain old telephone service (POTS) to transport data, often at 10 kbps or less. As the video industry pushes the limits of higher bandwidth and increased compression, Caltrans must monitor whether the next-generation video encoders will be able to function in low-bandwidth conditions.

Caltrans needed equipment evaluation research under Caltrans rural operating conditions and environments to determine if CCTV video encoders would meet Caltrans performance measures.

Objectives

Several companies have next-generation video encoder equipment. Each company has a specification sheet that is often difficult to compare with their competitors. This project determined how this equipment performs under real-world Caltrans rural operating conditions including extreme temperatures, low bandwidth, and very remote locations.

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center determined and evaluated which next-generation video encoder equipment would be viable as rural ITS field equipment options as Caltrans adds to and refreshes its ITS assets.

An evaluation is provided based on performance of the chosen video encoder equipment. Details of this evaluation are documented herein, and have been provided to the members of the Rural Program Steering Committee (PSC) and to districts, along with a demonstration of next-generation technologies. Districts have continued evaluating and using the next-generation video encoder equipment during their normal day-to-day operations.

One of the primary goals of this research is to characterize how the selected encoding devices can perform under a variety of network conditions, especially under the low-bitrate, high-error conditions that are common at rural field element sites. A secondary goal is to review other relevant features of the devices that make impact its applicability to different types of sites. The purpose of these goals is to facilitate future device selection for various sites, given their particular network conditions and other attributes.

How well a video stream performs under different network conditions is primarily a function of the configurability and feature set of the encoding device. A poor choice of decoder on the stream-consuming end can also affect the stream quality of course. However the streaming protocols supported by the devices under consideration do not dynamically adapt to feedback from the decoder so, as long as the decoder is stable and fully supports the encoding mode being used, its impact on stream quality should be minimal.

Characterizing how the video streams from a given encoding device may perform under various network conditions involves carefully considering the device's range of features and relevant configuration parameters. First, we will explore these features and parameters for each selected device, examine how varying network conditions may affect the resulting stream, and present qualitative and quantitative data collected during testing in order to facilitate optimal device configuration for sites of various types. Second, we will draw comparisons between devices and their range of encoding modes and parameters and other features in order to facilitate optimal device selection for sites of various types.

Scope

As part of the kickoff meeting and subsequent discussions, based on Project Panel inputs and direction, AHMCT identified Caltrans rural operating conditions and gaps related to CCTV encoder systems. This included field conditions as well as characteristics of rural communications channels for the resulting images. AHMCT identified known gaps related to Caltrans use of CCTV encoders in rural environments, as well as the categories of CCTV encoder systems to be evaluated in the following research tasks. Where feasible, the report identified specific CCTV encoder systems to evaluate in a prioritized list. This report summarizes the test methodology and results for the controlled testing of CCTV encoder systems.

Controlled Testing Goals, Issues, and Overview of Approach

One of the primary goals of this research was to characterize how the selecting encoding devices can perform under a variety of network conditions, especially under the low-bitrate, high-error conditions that are common in connections to rural field element sites. A secondary goal was to review other relevant features of the devices that may impact its applicability to different types of sites. The overall purpose was to facilitate future device selection for various sites, given their particular network conditions and other attributes.

How well a video stream performs under different network conditions is primarily a function of the configurability and feature set of the encoding device. A poor choice of decoder on the stream-consuming end can also affect the stream quality of course. However, the streaming protocols supported by the devices under consideration do not dynamically adapt to feedback from the decoder, so as long as the decoder is stable and fully supports the encoding mode being used its impact on stream quality should be minimal.

Characterizing how the video streams from a given encoding device may perform under various network conditions involves carefully considering the device's range of features and relevant configuration parameters. First, we explored these features and parameters for each selected device and examined how varying network conditions may affect the resulting stream. Herein, we present qualitative and quantitative data collected during testing in order to facilitate optimal device configuration for sites of various types. We then draw comparisons between devices and their range of encoding modes and parameters and other features to facilitate optimal device selection for sites of various types.

The researchers identified additional camera(s) for bench testing. Due to delays from the COVID-19 pandemic, which was in full force through much of this research, the bench testing took longer than anticipated. Access to the lab was limited for much of the period, so that methodologies were needed to perform meaningful lab testing remotely. This also impacted the rural field testing. At the completion of this task, there was insufficient time for meaningful rural field testing by Caltrans personnel, and insufficient time for them to prepare for the testing. Upon conferring with the project manager, it was decided to omit rural field testing. Several camera systems were procured to support testing of additional models, and some of these were tested. Procurement time for some of the cameras was far longer than ordinary, so these systems were not tested. One vendor indicated a six-month time of arrival, which would have allowed for testing. However, this camera had not arrived after nine months due to COVID19-related supply chain issues, and AHMCT canceled this order to avoid billing beyond the contract period.

Chapter 2: Devices Tested

The devices selected for testing are shown in Table 2.1. A wider range of devices to evaluate was considered, in particular some standalone single-channel encoders, but the candidates were disqualified for various reasons. Some of the candidates were unavailable for purchase or loan, largely due to supply-chain issues related to the COVID-19 pandemic. One device (an Axis Q8685-E) was ordered and did not arrive until well beyond the testing period. Other candidates had reached end-of-life status before the acquisition phase of the project, e.g. the Axis Q7411, Axis Q7424-R Mk II, Axis Q6055-E, and Axis Q6155-E.

Table 2.1: Devices selected for testing

Device	Type	Part #	Firmware Version
Axis Q8752-E	CCTV camera with integrated encoder	01838-001	10.12.153
Bosch MIC inteox7100i	CCTV camera with integrated encoder	MIC-7602-Z30GR	8.46.0030
CostarHD RISE4260HD	CCTV camera with integrated encoder	4261-1000	Core 4.1.92, Rise 4.1.323
WTI Viper/SidewinderHD	CCTV camera with integrated encoder	VS720-H.264-HD30L-POE-R	2.15.0.r

One transcoder device (WTI Hydra 265) was considered for evaluation, but evaluating a transcoder would have required the development of a testing scenario distinct from that used for the other devices and, since no district expressed interest in this device during Task 3, it was excluded from evaluation.

Despite the small size, the device selection provides good coverage of the more widely used brands in highway surveillance (Axis, Bosch, CostarHD, WTI), a broad range of resolutions, frame rates, compression standards, and bitrate control modes. It is also expected that the streaming features and characteristics of the selected devices will prove similar to those of many other devices of the same branding, since devices under the same brand umbrella commonly share similar encoding hardware and software, being differentiated primarily by other features and specifications (resolutions, imaging sensors, object detection ability, wipers, heaters, environmental specifications, power supply compatibility, and similar).

Axis Q8752-E Bispectral Camera

The Axis Q8752-E is a Pan-Tilt-Zoom (PTZ) Closed-Circuit Television (CCTV) camera with an integrated encoder and Ethernet interface for streaming via Transmission Control Protocol/Internet Protocol (TCP/IP). It features:

- both visual and thermal cameras
- image stabilization
- image analytics and activity detection functionality
- a broad range of resolutions from 160x120 to 1920x1080
- H.264, H.265, and Motion JPEG (M-JPEG) video streaming via Real-Time Streaming Protocol (RTSP)
- M-JPEG streaming via Hypertext Transfer Protocol (HTTP).
- single frame fetch via HTTP
- video stream bitrate control modes: include Average Bitrate (ABR), Maximum Bitrate (MBR), and Variable Bitrate (VBR). ABR mode supports an optional maximum bitrate parameter.

The Axis Q8752-E, like most recent Axis devices, also supports a proprietary stream processing and management system called Zipstream whose advertised purpose is primarily to reduce the bitrate and storage requirements of video streams. Other features include dynamic Group of Pictures (GOP) interval and dynamic frame rate.

Figure 2.1: Axis Q8752-E bispectral camera

Bosch MIC inteox 7100i Camera

The Bosch MIC inteox 7100i is a PTZ CCTV camera with an integrated encoder and Ethernet interface for TCP/IP streaming. It advertises the following features~[1]:

- rugged construction
- excellent low-light sensitivity
- high dynamic range
- image stabilization
- intelligent video analytics, including detection of traffic incidents, wrong-way drivers, pedestrians, slow and stopped vehicles, etc.
- automatic detection and PTZ tracking of objects
- local storage via Secure Digital (SD) card
- third-party app support
- Open Network Video Interface Forum (ONVIF) compatibility

It supports five streaming resolutions from 512x288 to 1920x1080, single-frame fetch via HTTP, and video streaming via H.264, H.265, and M-JPEG over RTSP. Other features include an automatic GOP interval mode and preconfigured streaming profiles for a variety of network types.

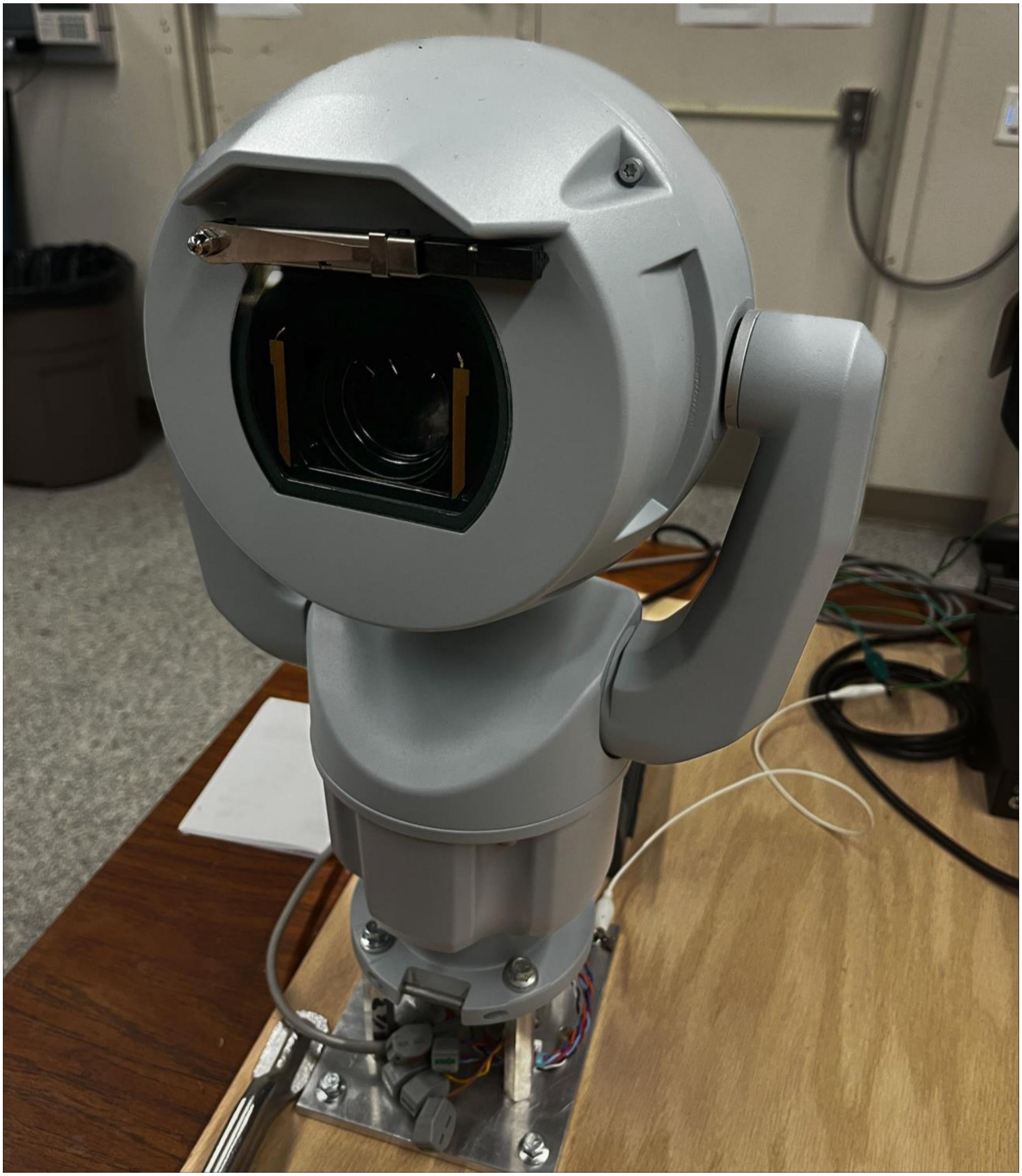

Figure 2.2: Bosch MIC inteox 7100i camera

CostarHD RISE 4260HD Camera

The CostarHD RISE 4260HD is a PTZ CCTV camera with an integrated encoder and Ethernet interface for TCP/IP streaming. It advertises the following features~[2]:

- extreme low-light sensitivity
- wide dynamic range
- electronic image stabilization
- defog/dehaze image processing

It supports seven streaming resolutions from 160x120 to 1920x1080, single-frame fetch via HTTP, and video streaming via H.264 and M-JPEG over RTSP.

Figure 2.3: CostarHD RISE 4260HD camera

WTI Viper/Sidewinder HD Camera

The WTI Viper/Sidewinder HD is a PTZ CCTV camera with an integrated encoder and Ethernet interface for TCP/IP streaming. It advertises the following features~[3]:

- wide dynamic range
- defog mode
- electronic image stabilization

It supports nine streaming resolutions from 320x240 to 1920x1080 and video streaming via H.264, MPEG-4, MPEG Transport Stream (MPEG-TS), and M-JPEG over RTSP.

Figure 2.4: WTI Viper/Sidewinder HD camera

Chapter 3:
Test Methodology

Two types of testing were performed in this study: video stream testing, and static image testing. While the aim of this research primarily relates to video streaming, each Caltrans district makes extensive use of static images, acquired by means of periodic fetches from CCTV encoders at field element sites via the Caltrans CCTV Information Relay located in each district. For many rural CCTV sites which do not have the network capacity to support a useable video stream, generating and transferring these static images is the principal mode of use. Typically, these images are encoded in JPEG format and fetched from the encoder using HTTP or Hypertext Transfer Protocol Secure (HTTPS). Since this remains an important use case for highway surveillance CCTV encoders, static image testing was included in this research.

In this study, data was collected and analyzed from a total of 29,670 video tests and a total of 2,926 static image tests (32,596 tests overall).

Stream Encoding Overview

To understand the results of the video streaming tests, the reader will need to be familiar with some basics of video streaming technology.

Before encoding for streaming purposes, digital video can be thought of as a series of images occurring one after another in time, usually at a constant rate. Each of these images is essentially a rectangular matrix of pixels, with each pixel consisting of a value representing the color of that pixel. Each video stream is associated with a particular "color space," which is a scheme that determines how each particular pixel value is mapped to its actual, intended color. Many such color spaces exist, several are in common use today.

Video Compression Standards

Video scenes usually contain a high degree of redundant content, both intra-frame (e.g., areas of low detail or texture), and inter-frame (e.g., stationary objects or backgrounds). As such, transmitting a video stream by simply sending each video frame directly in succession usually creates an inefficient, low-entropy bitstream that consumes far more bandwidth than is actually required. At high camera resolutions and frame rates, the bitrate for such streams can quickly become impractical for use over many commonly-used data transmission systems. To overcome this, video streams are typically compressed. A variety of compression standards exist, but the ones most commonly used by today's CCTVs and video encoding devices are:

- MPEG-4 (MPEG-4 Part 2)
- H.264 (ITU-T Recommendation H.264; MPEG-4 Part 10), also commonly called Advanced Video Coding (AVC)
- H.265 (ITU-T Recommendation H.2645; MPEG-H Part 2), also commonly called High Efficiency Video Coding (HEVC)
- M-JPEG

MPEG-4 is an older standard that is quickly becoming obsolete for this application. H.264 and H.265 are more modern, and are also the two most commonly used. M-JPEG is an unsophisticated scheme for the transmission of a series of video frames, each encoded in the Joint Photographic Experts Group (JPEG) image format. Although JPEG can compress images fairly efficiently, M-JPEG takes no advantage of inter-frame redundancies, resulting in streams that are usually far less efficient than those using MPEG-4, H.264, or H.265.

Today, MPEG-4 and M-JPEG are usually only chosen for reasons of compatibility with older software or older decoding hardware, while H.264 and H.265 are widely used. M-JPEG is also sometimes chosen when available H.264 or H.265 implementations are not sufficiently configurable to produce functional low-frame-rate video at very low bitrates such as those required for transmission over ISDN/POTS links. H.265 is considered to supersede H.264 although, at the time of this writing, H.264 still holds a compatibility advantage. However, when compatibility or decoder performance limitations are not an issue, H.265 is generally chosen over H.264 as it tends to produce more efficient streams.

Video Compression Profiles

Many video compression standards define a variety of "profiles" — combinations of features, behaviors, and color spaces — that affect how the streams are encoded. Commonly-used profiles for MPEG-4, H.264, and H.265 are:

- MPEG-4
    - Advanced Simple: supports interlaced video, B-frames, and more
    - Simple: a subset of Advanced Simple, intended for use especially in low-bitrate applications
- H.264
    - Baseline: supports only a subset of H.264 encoding features, allowing for simpler and less CPU-intensive decoding
    - Main: supports most H.264 encoding features; decoding is usually more CPU-intensive than Baseline

- High: supports nearly all H.264 encoding features; often produces more efficient, higher-quality streams; decoding is usually more CPU-intensive than Main

- H.265
    - Main: currently the most commonly used profile for H.265
    - Main 10: primarily adds support for 10-bit color
    - (more profiles available in newer versions)

In addition to profiles, some compression standards support a variety of "tiers" and "levels." However, as these are typically not directly configurable by the user for the types of encoding devices in this study, we will not consider them further.

Frame Types and GOP

As mentioned above, digital video can be thought of as series of images occurring one after another in time. In order to efficiently encode a stream, most compression standards take advantage of inter-frame redundancies. MPEG-4, H.264, and H.265 do this by encoding the frames of a video stream in different ways depending on whether they reference other frames and how they do so. This is referred to as the "frame type." The three most common frame types are I-frames, P-frames, and B-frames.

I-frames (intra-coded frames, a.k.a. key frames) are encoded in a way that contains only intra-frame references (references to data in the same frame). They do not contain inter-frame references (references to data in other frames in the stream).

P-frames (predicted frames, a.k.a. delta frames) are encoded in a way that contains intra-frame references, as well as inter-frame references to data in previous frames in the stream.

B-frames (bidirectional predicted frames) are encoded in a way that contains intra-frame references, as well as inter-frame references to data in both previous and subsequent frames in the stream.

Since I-frames contain only intra-frame references, they can be independently decoded. Decoding P-frames and B-frames, however, requires processing a sequence of frames. Using a high number of P- and B- frames usually results in a significant increase in stream efficiency. However, due to their dependence on other frames, stream quality and resiliency issues can result when streaming over network links prone to data loss or corruption.

A GOP is a series of frames that begins with an I-frame followed by zero or more non-I-frames. Non-I-frames are usually significantly smaller than I-frames so, generally, the longer the GOP, the more efficient the encoding. However, this efficiency comes with trade-offs: when streaming data loss occurs, the stream is often corrupted until the next I-frame is received by the decoder. The number of frames in a GOP is referred to as the GOP interval. If this interval is very long, the stream may take a long time to recover from data loss. In addition, for recorded streams, long GOPs can make seeking more difficult, since many playback applications will only allow seeking to an I-frame. Thus, selecting an appropriate number of frames often involves a compromise between stream efficiency, stream recovery time, and "seekability." Most encoders allow GOP interval to be specified by the user as a fixed value for a particular stream. However, many encoders also have a "dynamic GOP" mode which attempts to optimize the stream efficiency by automatically adjusting the GOP interval based on scene conditions. Depending on the implementation, this latter mode may not be a good fit for streaming over lossy networks unless it allows a maximum GOP interval to also be specified in order to limit stream recovery time.

Video Stream Control and Transports

A variety of protocols exist for video streaming. However, many of these are better suited to playback of recorded streams that have been pre-encoded at several different bitrates, and involve larger buffers and latencies that may not be acceptable for use in real-time surveillance applications. For "backhaul" (field-to-office) streams from real-time surveillance cameras, RTP over User Datagram Protocol (UDP) remains one of the most widely used protocols. RTP can work over Transmission Control Protocol (TCP) as well (often done to ease firewall traversal), but it tends to be less efficient, can sometimes perform very poorly over very limited network connections, and cannot be used for multicast streaming.

Bitrate Control

Most encoder devices support multiple mechanisms to balance a stream's quality with its bitrate. This is usually necessary since available bandwidth and storage (if recording) are not unlimited. A number of such mechanisms are in common use, and some devices also support additional proprietary schemes which can aid in managing stream bitrates. In addition, even the common mechanisms are often defined and implemented differently across vendors, making a precise definition difficult. However, the following simplified descriptions should be generally helpful:

- Constant Bitrate (CBR)[1]: CBR is a relatively simple and widely supported bitrate control mode. With CBR, a bitrate is specified and the encoder

[1] Not to be confused with Capped Bitrate which is also referred to as CBR

encodes the stream to that bitrate. Since the bitrate does not dynamically adapt to the video contents, CBR bitrates are easily predictable, but often result in higher bandwidth and storage requirements than other bitrate control modes.

- Maximum Bitrate (MBR)[2]: MBR is a relatively simple bitrate control mode that generally allows a stream to use whatever bitrate is necessary to maintain its natural quality, unless that bitrate would exceed a specified maximum level, in which case it employs a mechanism to reduce the bitrate (usually an increased compression level).
- Average Bitrate (ABR)[3]: ABR is a more complex bitrate control mode that allows for a target bitrate to be specified. The stream is continuously analyzed and compression is tuned in order to keep the stream's bitrate close to the specified target. Some ABR implementations also allow a maximum bitrate to be specified.
- Variable Bitrate (VBR): VBR allows the stream's bitrate to vary as needed in order to maintain its natural quality. VBR is often used when quality is the most important aspect of the stream. It can make a stream's bandwidth unpredictable, and the encoding process more compute-intensive. These characteristics make VBR an unlikely candidate for highway surveillance streams, especially in the rural setting. Some VBR implementations also allow a maximum bitrate to be specified.

It is worth mentioning that device implementations of these bitrate control modes often operate on a "best effort" basis, treating their specified bitrate values (e.g., target, maximum) as suggestions rather than strict requirements. If the user specifies impractical values for these parameters, the bitrate of the resulting stream will possibly be quite far from those values.

Finally, in addition to the above bitrate control modes, there are a number of more modern schemes which allow for streams to adapt to network conditions and client/decoder characteristics. In addition to support on the server/encoder end, these adaptive schemes typically require support on the client/decoder end as well. One of these is the HTTP Live Streaming (HLS) protocol. Another is Dynamic Adaptive Streaming over HTTP (DASH). However, in the context of CCTV surveillance, these approaches are more commonly employed further downstream, usually in transcoders and video servers (in preparation for distribution of streams to multiple consumers), not at the field

[2] Not to be confused with Multi-Bitrate which is also referred to as MBR

[3] Not to be confused with Adaptive Bitrate which is also referred to as ABR

element site. They are rarely supported by the type of CCTV encoding devices under consideration, and thus were not covered in this research.

Testing Setup

The testing was carried out in an AHMCT laboratory. A 4K display was placed on a table at one end of the room, and the CCTV devices were arranged on another table at a sufficient distance from the display to allow for clear focus on the image shown on the display. This configuration is illustrated in Figure 3.1.

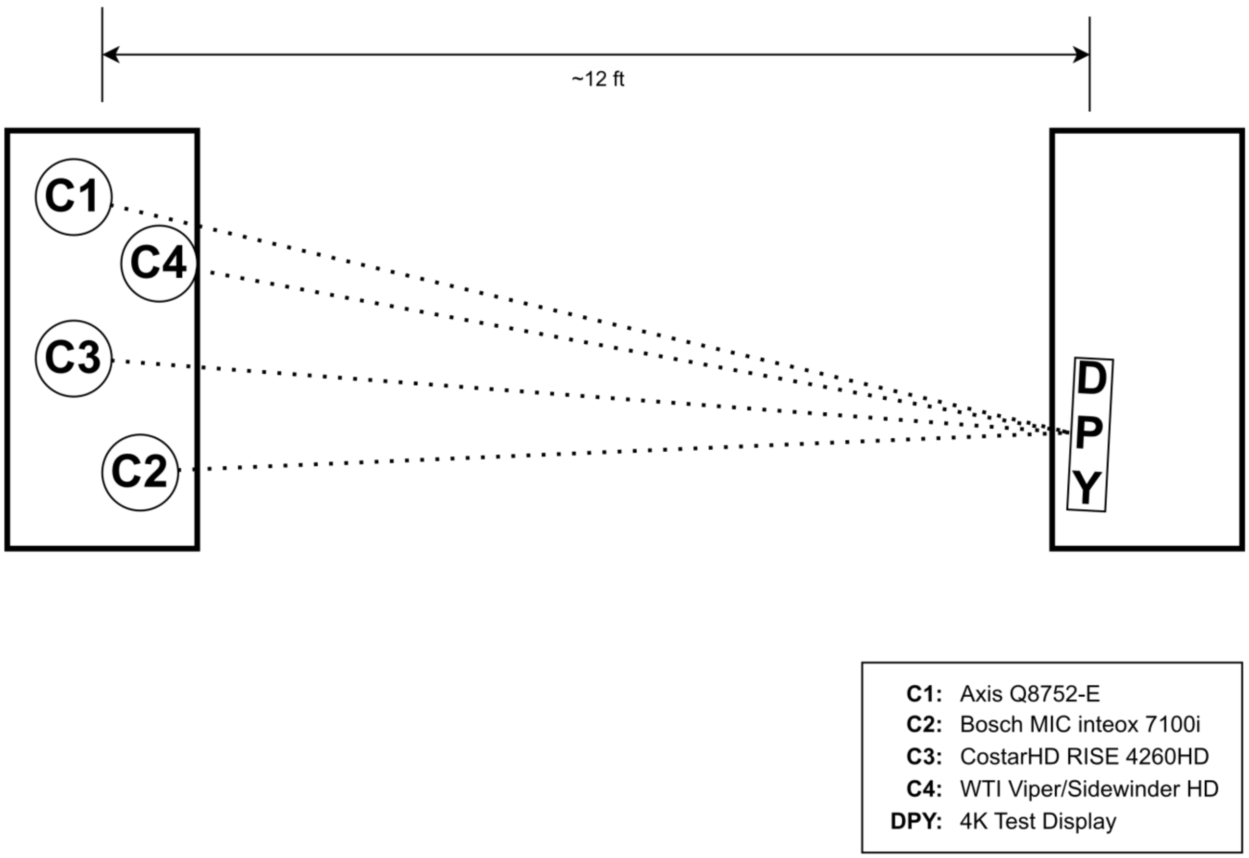

Figure 3.1: Test setup

Figure 3.2: CCTV devices mounted for testing

Figure 3.3: CCTV devices aimed at the test display

The testing process was orchestrated by a computer named “Test Manager”. Another computer, named “Device Manager”, was used for initial setup and various diagnostic purposes. These two computers were connected to a network segment named the “sink” segment via a Gigabit Ethernet switch. The CCTV devices’ Ethernet interfaces were connected to a network segment named the “source” segment via another Gigabit Ethernet switch. The “source” and “sink” network segments were bridged by the Network Simulator, a computer that used the traffic control subsystem of the Linux kernel to manipulate ethernet traffic across the bridge in order to simulate a network link experiencing various types of network traffic conditions. The Network Simulator also recorded network traffic statistics for our tests. This network architecture is illustrated in Figure 3.4.

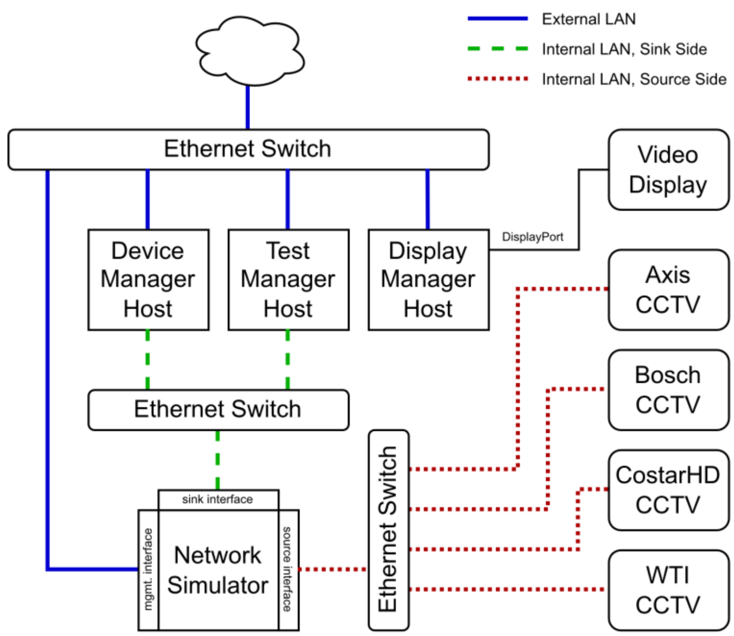

Figure 3.4: Test lab network architecture

Video Stream Testing

Each of the devices tested supports a variety of streaming configuration parameters. For example, each of the devices supports its own unique set of features such as:

- streaming protocols: RTP with RTSP, HTTP
- transports: UDP, TCP
- resolutions: from 160x120 to 1920x1080
- frame rates: 0.5 frames per second (FPS) to 30 FPS
- frame rate modes: fixed, dynamic
- compression standards: M-JPEG, MPEG-4, H.264, H.265
- compression standard profiles: Baseline, Main, and High for H.264; Main for H.265
- GOP modes: fixed, dynamic
- GOP frame type modes: IP, IBP, etc.
- standard bitrate control modes: CBR, MBR, ABR, VBR

- other bitrate management features: Axis Zipstream, CostarHD constrained mode

Testing and comparing every possible combination of these parameters would be neither feasible nor helpful. Furthermore, since not every device supports the same configurations, many of these configurations are not directly comparable across devices.

A practical testing approach was needed that would keep the dimensionality of the testing matrix low enough that the testing could be completed in weeks to months (rather than years) while also allowing the impact of these various features and configurations to be characterized and meaningfully compared between devices.

It was observed that all the devices under consideration had common support for a similar "vanilla" streaming mode, often as the default. This mode has the following characteristics in common across the devices:

- RTSP streaming via Real-Time Transport Protocol (RTP) over UDP
- H.264 using "Main" profile
- fixed GOP interval of about 30 frames
- a bitrate control mode that allows a target bitrate to be specified (e.g., ABR, CBR)
- fixed (i.e., non-dynamic) frame rate

It was decided to use this mode as a "baseline" for each device, and to independently compare the device's various features and parameters of interest to it, in order to evaluate their individual impacts on the characteristics of the resulting streams. This "baseline" mode would also serve as a useful comparison point to evaluate significant differences in basic streaming behavior between devices.

Scene Selection

Video streaming performance is heavily dependent on scene activity, which is a function of site activity, light levels, zoom value, and other factors. This complicates the selection of test scenes. Selecting a test scene with a lower level of activity than expected could result in an insufficient estimate of the required streaming bandwidth for a site.

A range of scenes with varying levels of activity could be chosen for testing, but it is not clear how the resulting differences in streaming characteristics and bitrates for these scenes could be used to inform a decision for a particular real-world site. Furthermore, each addition of a scene to the testing protocol would increase the number of test cases by 100%. So, it was decided to carefully select a single scene for testing.

Since this project had a particular focus on evaluating device performance in low-bandwidth, rural network conditions, and since, even if a site is very inactive, it is unacceptable for the stream to drop out every time something significant occurs, a test scene was chosen that represents a reasonably active and constant site, with the expectation that the level of activity in this scene would be at the high end of what would be expected for most rural sites. Sites with higher activity levels than our chosen test scene are likely to be urban sites with higher-grade network connectivity.

Figure 3.5 displays four still frames from the chosen scene, chosen to demonstrate its varying traffic activity. The scene duration is 40 seconds.

Figure 3.5: A selection of still frames from the video test scene (all still images are selected from the video [5.5 4K Camera Road in Thailand No 2 (https://www.youtube.com/watch?v=F4bICvLY024)](https://www.youtube.com/watch?v=F4bICvLY024)

Network Link Classes

In order to test how the streams from the CCTV devices perform in a variety of network conditions, we sought to define a number of "link classes" to approximate the network rates common to field element site uplinks. After consulting with the panel for this project, we settled on link classes in Table 3.1.

Table 3.1: Link classes

Link Class	Typical Use	Nominal Rate (kbps)	80% Rate (kbps)	80%x80% Rate (kbps)
1	POTS Modem	9.6	7	6
2	POTS Modem	14.4	11	9
3	POTS Modem	28.8	23	18
4	POTS Modem	33.6	26	21
5	POTS Modem	56	44	35
6	ISDN BRI	128	102	81
7	2G	256	204	163
8	DSL, 3G	512	409	327
9	DSL, 3G	768	614	491
10	cable, 4G, 5G, Ethernet, µwave	1000	800	640
11	cable, 4G, 5G, Ethernet, µwave	2000	1600	1280
12	cable, 4G, 5G, Ethernet, µwave	4000	3200	2560
13	cable, 4G, 5G, Ethernet, µwave	8000	6400	5120

The rates in the third and fourth columns represent the nominal rate with "safety" margins applied. A rule of thumb for video stream planning is to use apply a 20% safety margin to the nominal link rate to allow for regular fluctuations (e.g., due to other traffic) in the link capacity. This is the 80% rate (rounded down to its integer value) in the third column.

Furthermore, another rule of thumb, especially for bitrate control modes that allow the specification of a target value such as ABR, is to apply another 20% safety margin (on top of the 80% rate) to allow for natural fluctuations in the bitrate of the stream. For example, if we specify a target rate of 640 kbps for the stream, the stream rate could increase to 800 kbps before exceeding our safety margin. This is the 80%×80% rate (rounded down to its integer value) in the fourth column. Once these values are established, the 80% value provides a starting point for selecting a maximum bitrate (for bitrate control modes that allow maximum bitrate to be specified, e.g., MBR and some variants of ABR and VBR), and the 80%×80% value provides a starting point for selecting a target bitrate (for bitrate control modes that allow target bitrate to be specified, e.g., ABR, CBR), as illustrated in Figure 3.6.

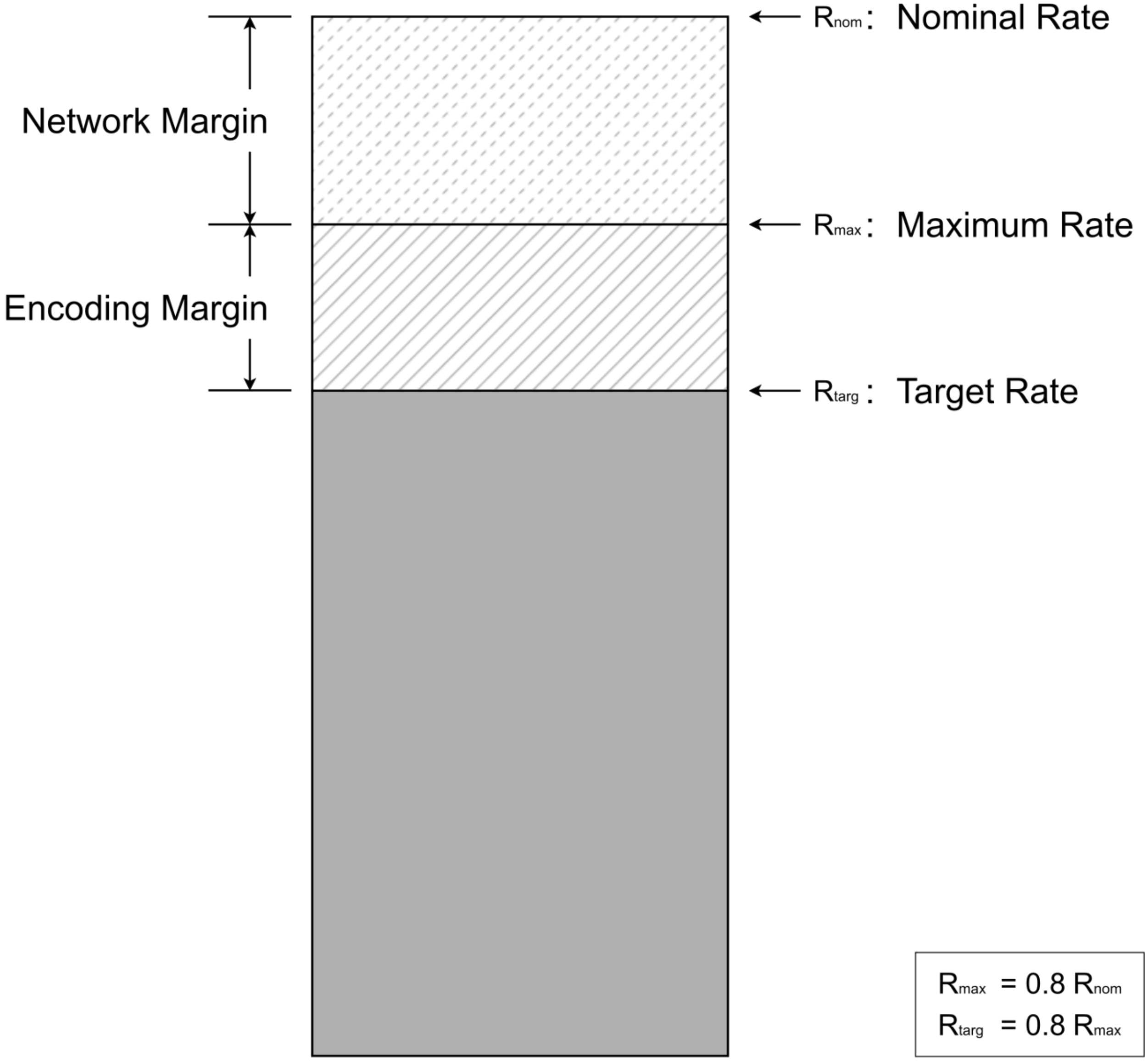

Figure 3.6: Bitrates and safety margins

Resolution Classes and Frame Rates

Resolution Classes

Each of the devices in this study supports a unique set of video and image resolutions. To increase comparability between the test results of the devices, we grouped the resolutions from each device into classes based on the number of pixels represented. Examining the distribution of resolutions by pixel count, five thresholds were selected to form six classes with roughly similar pixel counts, as shown in Figures 3.7 and 3.8.

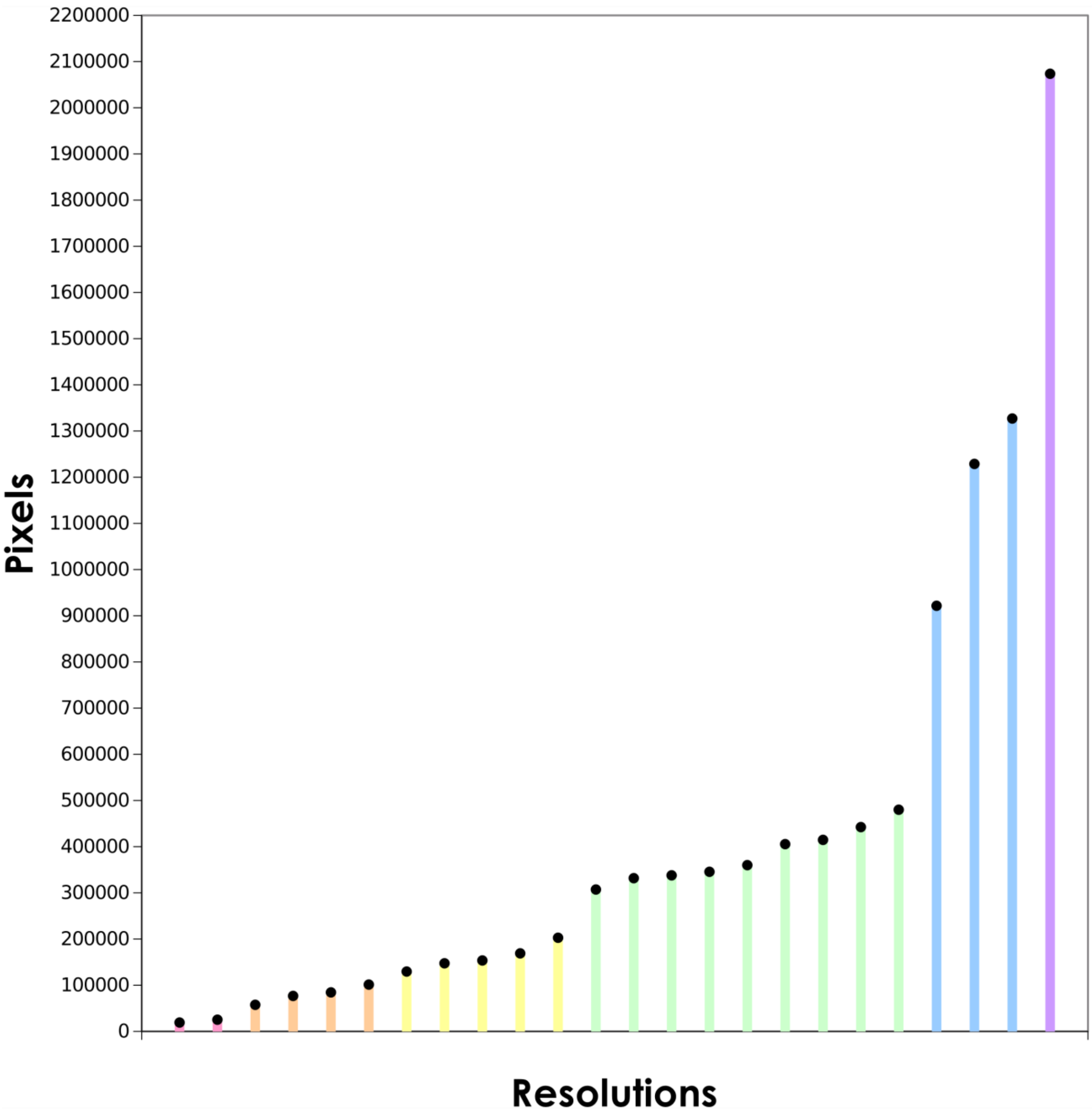

Figure 3.7: Resolution classes and distribution by pixel count

Class	Resolution	Pixels	Aspect Ratio	Axis	Bosch	Costar	WTI
1	160x120	19200	4:3	⬡		⬡	
	176x144	25344	11:9	⬡			
2	320x180	57600	16:9	⬢			
	320x240	76800	4:3	⬡			⬢
	352x240	84480	22:15			⬢	⬡
	352x288	101376	11:9	⬡			
3	480x270	129600	16:9	⬢			
	512x288	147456	16:9		⬢		
	640x240	153600	8:3				⬢
	704x240	168960	44:15				⬡
	704x288	202752	22:9	⬡			
4	640x480	307200	4:3	⬡	⬡	⬡	⬡
	768x432	331776	16:9		⬢*		
	704x480	337920	22:15	⬡	⬡		⬢
	720x480	345600	3:2		⬡	⬢	⬡
	800x450	360000	16:9	⬢			
	704x576	405504	11:9	⬡	⬡		
	720x576	414720	5:4	⬡	⬡	⬡	
	768x576	442368	4:3	⬡			
	800x600	480000	4:3	⬡			
5	1280x720	921600	16:9	⬢	⬢	⬢	⬢
	1280x960	1228800	4:3	⬡			
	1536x864	1327104	16:9		⬡		
6	1920x1080	2073600	16:9	⬢	⬢	⬢	⬢

* This table reflects the full set of resolutions supported by the hardware/firmware versions used for testing. However, our Class 4 resolution choice for the Bosch MIC inteox 7100i was made using an earlier version of the firmware for this device. Were we to repeat the testing today, we would select 720x480 to represent this resolution class for this device.

⬡ supported but not chosen
⬢ supported and chosen

Figure 3.8: Resolution classes

While the resolutions in Class 2 could conceivably be useful in some sites with extremely low-rate network connections, the resolutions in Class 1 are so low as to be of little use. We therefore removed Class 1 from consideration, leaving five resolution classes — 2 through 6 — for testing.

From each of these classes, one resolution was chosen (if supported) from each device. In order to enhance comparability of test results between devices, the resolutions in each class were chosen such that their pixel counts were in reasonable proximity to each other, without consideration of aspect ratios or how “standard” the resolutions may be.

Frame Rates

The selection of a set of common frame rates between devices was more straightforward. To keep the matrix of test cases from growing too large, we limited testing to five frame rates. 30 FPS is a common standard, it is supported by all the devices, and thus it was included. Since a major aim of this research is evaluate how these devices perform in rural field settings, it was desired to include a number of low-end frame rates. For these, we selected 1, 2, and 5 FPS. Finally, to bridge the gap between these two extremes, we chose 15 FPS, resulting in the full set of frame rates for testing: 1, 2, 5, 15, and 30 FPS.

Testing and Data Collection

In this study, our testing had two primary aims:

- To quantify the full bitrate of the video streams under undegraded network conditions
- To evaluate the performance of the video streams under degraded network conditions

We initially considered multidimensional network condition tests (throughput, latency, jitter, packet loss), but this would have added several more months to the testing period. In our experience, the network conditions most likely to cause video stream degradation (at least in the ITS setting) are reductions in throughput and the packet loss that ultimately results from it. So, for this study, it was decided to approximate network degradation solely by throttling the throughput of the link between the source (CCTV encoder) and the sink (the Test Manager host).

Data collection was automated by means of an application running on the Test Manager host. Testing involved repeating test cases under each of four network conditions managed by the Network Simulator:

- Non-limited: allow data to flow at the full rate of the encoding device’s network interface
- limited 100%: limit data flow to the full nominal rate (no degradation) of the link class
- limited 80%: limit data flow to 80% of the nominal rate of the link class
- limited 50%[4]: limit data flow to 50% of the nominal rate of the link class

[4] For communications links in the ITS setting, a wide range in network quality may be encountered. While there is sometimes a need to stream video over links that regularly

The non-limited case is designed to allow the stream's full average bitrate to be quantified, while the other three cases are designed to evaluate the stream's performance (frame loss, etc.) under various network throughput conditions (100%, 80%, 50% of nominal rate).

A high-level outline of the testing process is provided in Figure 3.9.

- For each device:
  - For each encoder configuration (encoding, control mode, etc.):
    - For each resolution class:
      - For each frame rate:
        - For each network link class:
          - Calculate R_{targ}, R_{max} for this link class (Figure 3.6) as applicable
          - For each network condition (ungoverned, 100%, 80%, 50%):
            - Calculate network throttle value (if any) for this link class and network condition
            - Configure network simulator
            - **Perform video streaming test (specifying R_{targ}, R_{max} as applicable)**

Figure 3.9: High-level outline of the testing process

Data Analysis

The primary goals of the data analysis phase were to determine, for each device:

- How do the various stream configurations tested compare with each other, especially in terms of bitrate and frame loss estimates?
- How well does the device tend to keep the stream bitrate within range of the specified target and/or maximum bitrate parameters?
- How do network bandwidth limitations affect the stream as received by the client/decoder?

experience extreme throughput degradation, we did not throttle below 50% in our testing for a couple reasons. First, for streams utilizing the majority of the nominal rate of a given link, degradations in throughput beyond 50% often result in exceedingly poor stream quality. Second, for links that regularly experience such drops in throughput, it's best (for stream configuration purposes) to simply treat the link as if its nominal rate were lower. For example, if a microwave link with a nominal rate of 2000 kbps regularly experiences 50% drops, it may be helpful to simply treat it as a 1000 kbps link and configure the video stream accordingly. Adaptive bitrate streaming protocols may help in these scenarios as well, but they are not widely supported by the types of devices reviewed in this study.

The first goal was accomplished by comparing statistics between the corresponding tests (i.e., equivalent resolution, frame rate, network condition and bitrate target/maximum parameters) in each test group being compared.

For the second goal, the measured stream bitrate for each test was compared to the target/maximum bitrate parameters and the test case was classified according to its relationship between these parameters. This classification was then visualized on a “stream quality analysis” chart (see Figure 3.10).

The third goal was accomplished by comparing the frames received in each of the network-limited tests to the frames received in the non-network-limited test. These comparisons were then used to estimate the frame loss due to each network limitation scenario, and these frame loss estimates were then used to classify the test case relative to how resilient it was to network limitations in terms of frame loss.

There is always some level of non-determinism involved in sequential testing. Test results may vary slightly when repeated due to minor differences in timing, encoder state, sporadic errors, and the like. Limited spot testing was performed in order to gauge the magnitude of these inter-test variances, and it was observed to be much smaller overall than the magnitude that would result from a change in test scene. The goals of this research involve characterizing the behavior of these devices at a macroscopic level, so these minor variances will not significantly affect the results.

To assist in visualizing the data collected from the thousands of tests performed in this study, a "stream quality analysis" chart was developed and generated for each applicable test group. An example (for an Axis test group) is shown in Figure 3.10.

Each cell in the table represents the results of four individual streaming tests performed at a particular resolution and frame rate (rows), for a particular link class (columns):

1. streaming over an ungoverned network link
2. streaming over a network link rate-limited to 100% of the link class's nominal rate
3. streaming over a network link rate-limited to 80% of the link class's nominal rate
4. streaming over a network link rate-limited to 50% of the link class's nominal rate

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6 7 6	14.4 11 9	28.8 23 18	33.6 26 21	56 44 35	128 102 81	256 204 163	512 409 327	768 614 491	1000 800 640	2000 1600 1280	4000 3200 2560	8000 6400 5120
320x180 @ 1 FPS	5 •	5 •	5 •••	5 •••	6 ••••	5 ••••	6 ••••	5 ••••	6 ••••	6 ••••	5 ••••	5 ••••	6 ••••
320x180 @ 2 FPS	7 •	8 •	9 ••	9 •••	9 ••••	8 ••••	8 ••••	9 ••••	9 ••••	8 ••••	9 ••••	8 ••••	9 ••••
320x180 @ 5 FPS	9 •	11 •	15 •	15 ••	15 •••	15 ••••	15 ••••	15 ••••	15 ••••	15 ••••	15 ••••	15 ••••	15 ••••
320x180 @ 15 FPS	14 •	20 •	24 •	26 ••	31 •••	33 ••••	30 ••••	33 ••••	34 ••••	33 ••••	33 ••••	33 ••••	33 ••••
320x180 @ 30 FPS	20 •	24 •	40 •	41 •	43 ••	56 ••••	56 ••••	58 ••••	56 ••••	57 ••••	55 ••••	56 ••••	57 ••••
480x270 @ 1 FPS	5 •	8 •	11 ••	11 ••	11 ••••	11 ••••	10 ••••	11 ••••	11 ••••	10 ••••	11 ••••	11 ••••	11 ••••
480x270 @ 2 FPS	9 •	11 •	17 ••	18 ••	17 •••	17 ••••	18 ••••	18 ••••	17 ••••	18 ••••	17 ••••	17 ••••	17 ••••
480x270 @ 5 FPS	12 •	15 •	22 •	22 ••	27 •••	28 ••••	27 ••••	28 ••••	28 ••••	27 ••••	28 ••••	28 ••••	28 ••••
480x270 @ 15 FPS	21 •	25 •	35 •	39 •	47 ••	58 •••	63 ••••	62 ••••	60 ••••	61 ••••	63 ••••	61 ••••	63 ••••
480x270 @ 30 FPS	34 •	35 •	46 •	51 •	71 •	81 •••	100 ••••	102 ••••	96 ••••	104 ••••	100 ••••	102 ••••	100 ••••
800x450 @ 1 FPS	8 •	9 •	17 •	14 •	29 ••	32 ••••	29 ••••	31 ••••	30 ••••	30 ••••	29 ••••	30 ••••	30 ••••
800x450 @ 2 FPS	15 •	17 •	26 •	28 •	42 ••	47 ••••	50 ••••	49 ••••	52 ••••	48 ••••	52 ••••	48 ••••	49 ••••
800x450 @ 5 FPS	29 •	28 •	37 •	38 •	48 ••	74 •••	76 ••••	79 ••••	78 ••••	76 ••••	79 ••••	75 ••••	76 ••••
800x450 @ 15 FPS	58 •	58 •	58 ••	58 •	72 •	117 ••	149 •••	161 ••••	157 ••••	160 ••••	157 ••••	162 ••••	157 ••••
800x450 @ 30 FPS	86 •	83 •	86 •	87 •	95 ••	162 •	189 •••	252 ••••	258 ••••	262 ••••	254 ••••	263 ••••	265 ••••
1280x720 @ 1 FPS	18 •	17 •	23 ••	23 ••	32 •	75 •••	74 ••••	81 ••••	73 ••••	75 ••••	72 ••••	76 ••••	76 ••••
1280x720 @ 2 FPS	34 •	36 •	37 •	40 •	58 •	97 •••	126 •••	135 ••••	134 ••••	134 ••••	126 ••••	135 ••••	134 ••••
1280x720 @ 5 FPS	81 •	79 •	81 •	79 •	78 •	118 ••	109 •••	218 ••••	207 ••••	220 ••••	206 ••••	214 ••••	217 ••••
1280x720 @ 15 FPS	156 •	162 •	154 •	161 •	166 •	179 •	273 ••	315 •••	399 •••	399 ••••	395 ••••	409 ••••	395 ••••
1280x720 @ 30 FPS	216 •	224 •	231 •	212 •	221 •	232 •	325 •	433 ••	470 •••	531 ••••	640 ••••	614 ••••	627 ••••
1920x1080 @ 1 FPS	42 •	42 •	42 •	41 •	48 •	82 •••	111 •••	186 ••••	169 ••••	176 ••••	166 ••••	162 ••••	159 ••••
1920x1080 @ 2 FPS	76 •	80 •	80 •	74 •	77 •	122 ••	194 •••	308 •••	299 ••••	290 ••••	305 ••••	308 ••••	306 ••••
1920x1080 @ 5 FPS	177 •	191 •	142 •	172 •	189 •	190 •	247 ••	378 •••	464 •••	513 •••	534 ••••	549 ••••	515 ••••
1920x1080 @ 15 FPS	406 •	382 •	395 •	376 •	301 •	377 •	403 •	542 ••	688 ••	702 •••	962 ••••	966 ••••	998 ••••
1920x1080 @ 30 FPS	579 •	579 •	563 •	580 •	561 •	574 •	519 •••	661 ••••	903 •	1037 ••	1141 •••	1475 ••••	1464 ••••

R	: measured average bitrate (kbps)
R_{nom}	: nominal bitrate for link class (kbps)
R_{100}	: net-limit test rate (100% of R_{nom})
R_{80}	: net-limit test rate (80% of R_{nom})
R_{50}	: net-limit test rate (50% of R_{nom})
R_{max}	: specified max. rate (80% of R_{nom})
R_{targ}	: specified target rate (80% of R_{max})
F_r	: # frames received
F_e	: # frames expected

R	: $R \in [0, R_{targ}]$
R	: $R \in (R_{targ}, R_{max}]$
R	: $R \in (R_{max}, \infty)$
••••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	: $F_r \div F_e \geq 90\%$ for R_{100}
•	: $F_r \div F_e \geq 90\%$ for no test rates

Device:	Axis Q8752-E
Scene:	scene1
Encoding:	h264 main abr
GOP Mode:	30 f
Compression:	100
ZS Strength:	off

Figure 3.10: Example stream quality analysis chart

During testing, we calculate a "frame ratio" for each of the three rate-limited tests. We define "frame ratio" as the ratio of the number of frames received in a given rate-limited test case (items 2-4 above) to the number of frames received during its corresponding ungoverned test case (item 1 above). Defined this way, it is a proportional estimate of frame loss due to the network rate restrictions that were applied for the test case. It can thus be used to quantify the impact that real-world network link rate limits (nominal rate and drops due to congestion, etc.) would have on a video stream of the given configuration.

Each cell in the table has three indicators: a number, a color, and a set of 0-4 dots.

The number in the cell is the measured average bitrate for the ungoverned test.

The color of each cell corresponds to the ratio of the measured average bitrate of the ungoverned test to the specified target and maximum bitrates for that test. For encoding modes where both a target rate and a maximum rate are specified to the encoder, the meaning of the colors is as follows:

- Green: encoder kept the stream within the target bounds
- Yellow: encoder kept the stream within the maximum bounds but not the target bounds
- Red: encoder did not keep the stream within the maximum bounds

For encoding modes where only a maximum rate is specified to the encoder, the meaning of the colors is as follows:

- Green: encoder kept the stream within the maximum bounds
- Red: encoder did not keep the stream within the maximum bounds

The dots below the number in the cell represent the "frame ratio" results of the three rate-limited tests, and indicate the first rate-limited test (if any) for which the "frame ratio" fell below 90%:

- Four dots (••••) signifies that the frame ratio was above 90% for all three rate-limited tests
- Three dots (•••) signifies that the frame ratio was above 90% for the 100% and 80% link rate tests, but fell below 90% for the 50% test
- Two dots (••) signifies that the frame ratio was above 90% for the 100% link rate test, but fell below 90% for the 80% test
- One dot (•) signifies that the frame ratio was below 90% for even the 100% link rate test
- Zero dots signifies that a frame ratio was unable to be calculated due to test failure

Many of the tests performed poorly, both in terms of bitrate and frame ratio. This is because all row and column combinations were tested, even when impractical for the stream configuration being tested, and the bitrate control implementations of many encoders do not adhere strictly to the specified target and maximum bitrate parameters, especially when those parameters are impractical.

Furthermore, some encoding modes on some devices produce bitrates that are nearly always above the specified maximum rate. This seems to be an implementation decision, but the reasons for it are not clear. As one example to illustrate this, one test we performed for link class 10 (nominal rate 1000 kbps) requested a 1920x1080, 5 FPS stream with a target rate of 640 kbps and a maximum rate of 800 kbps. The encoder responded with a stream averaging 839 kbps, a rate that is above both the target and maximum rates. However, it's clear that the encoder is able to produce a stream within the bounds requested because, during the corresponding test for link class 9 (nominal rate 768 kbps, target rate 491 kbps, maximum rate 614 kbps), the encoder produced a stream averaging 606 kbps, a rate well within the target range of the test for link class 10.

The purpose of these tables is to aid in the stream configuration process and can help answer two key questions:

1. For a given resolution and frame rate, what are reasonable minimum values for target rate (if applicable) and maximum rate that will produce a reliable stream with this encoding?
2. For a communications link with a given nominal bitrate, what is the highest resolution and/or frame rate that can be streamed reliably with this encoding?

These tables help find approximate answers to these questions. Once that is done, the operator can use these answers as a starting point in tuning the stream until the visual quality is acceptable.

As an example of answering question #1, assume an operator would like to find minimum values for target and maximum rate for a 480x270 stream at 5 FPS using the device and encoding of Figure 3.10 (Axis Q8752-E, H.264 Main, ABR, GOP 30, compression 100, Zipstream off). The table row corresponding to this resolution and frame rate (row 8) would be followed from left to right until green cells with three or four dots are reached. In this case, the fifth column meets these criteria. It indicates that, for this configuration, the encoder produced a 27 kbps stream. The green color of this cell indicates that the average bitrate was within both our target (35 kbps) and maximum (44 kbps) rate values, and the three dots indicate that frame delivery remained good even when the 56 kbps communications link was restricted down to 80% of its nominal rate. Therefore, the target and maximum bitrates corresponding to this column are likely to be reasonable minimum values for a stream similar to (or less complex than) our test stream, over a network connection that may fluctuate down to 80% of its nominal rate, while still allowing an additional streaming headroom of 20% to accommodate sudden bitrate jumps due to changes in the scene. If the network connection is very reliable and is deemed unlikely to fluctuate below its nominal rate, then the cells with two dots may also be a reasonable choice.

As mentioned above, a red cell doesn't always mean that a stream is impractical for given resolution, frame rate, and desired bitrate. Some devices consistently overshoot the specified parameters. When this happens, it's possible to compensate for this bias. If a table row for a particular resolution and frame rate has no cells indicating desirable characteristics, then the measured bitrate in that cell can be used to determine potentially reasonable minimum values for target and maximum rate for that scenario. For example, if a cell indicates an average bitrate of 2345, then a target value of 2345 kbps and a maximum value of, say, 2345/80% = 2931 kbps may be a reasonable starting point for testing this streaming configuration.

Once reasonable minimum values are found for target and maximum rate, the stream produced with those parameters should be examined for visual quality. Since these rate values are minimums, they will typically produce a stream on the low end of the visual quality scale. Target and maximum rate values that produce a stream of acceptable visual quality can then be determined by iteratively increasing these values and examining the resulting stream.

Similarly, question #2 can be answered by following, from bottom to top, the column corresponding to the desired nominal rate (R_{nom}), bearing in mind that the rows are grouped by resolution first, then frame rate.

Stream quality analysis tables for all applicable streaming configuration test groups on each device in this study can be found in Appendix B. These stream quality analysis tables should be consulted during the stream configuration planning process, and they represent a key result of this study.

Areas of Focus

Compression Standards, Profiles, and Bitrate Control Modes

The choice of video compression standard, profile, and bitrate control mode can directly impact stream bitrates and quality. To allow for comparative analysis of their effect on streaming results, testing included several compression/profile combinations (when supported by the device):

- H.264 Main Profile
- H.264 High Profile
- H.264 Baseline Profile
- H.265 Main Profile

Testing also included several bitrate control modes:

- ABR
- MBR
- CBR
- VBR

M-JPEG

Comparing M-JPEG streams to H.264 and H.265 streams is not particularly worthwhile, other than to make a few general observations. While M-JPEG is a streaming protocol and can even be used over RTP, it is an extremely inefficient choice since it takes no advantage of inter-frame redundancies. This means that every frame is effectively a "key" frame, containing 100% of the data needed for its rendering.

On lossy or congested networks, M-JPEG is a particularly poor choice for UDP streaming since the larger average frame size results in a higher likelihood of corruption for each frame compared to streams which employ differential or predictive frames. However, M-JPEG is sometimes a reasonable choice for TCP streaming on lossy networks, particularly in cases where the integrity of each frame delivered is more important than the overall frame delivery rate. In addition, M-JPEG is sometimes used simply for compatibility with legacy software or devices. For this reason, since there are situations in which M-JPEG is still the right choice, it is included in the test scenarios to provide a general idea of the bitrates produced. Although M-JPEG is usually streamed over TCP, the tests were performed over UDP in order to give a cleaner estimate of the bitrates without having to factor in the contribution of TCP overhead (retransmission, congestion control, and the like). MJPEG is also used over POTS networks as a last resort. Often, other compression standards will not work on a POTS network and MJPEG will provide periodic image/frame refreshes.

GOP Intervals

Many encoding systems default to a fixed GOP interval of 30-60 frames. The reasoning behind this choice seems to be that it will result in a GOP interval duration of 1-2 seconds for standard 30 FPS streams. This means that if a single I-frame (key frame) happens to be lost or corrupted, the stream should recover within 1-2 seconds. However, for streams with lower frame rates, the average recovery time will be longer. For example, for a 5 FPS stream with a GOP interval of 30, the recovery time for a single lost or corrupted I-frame could be as long as 6 seconds. If poor network conditions result in loss or corruption of multiple consecutive I-frames, then recovery time can be much longer. The primary trade-off in GOP interval selection is as follows:

- higher GOP intervals tend to
  - result in lower bitrates, since I-frames (which are typically larger than other frame types) comprise a smaller portion of the stream
  - recover more slowly, since the duration between I-frames is longer
- lower GOP intervals tend to
  - result in higher bitrates, since I-frames (which are typically larger than other frame types) comprise a larger portion of the stream
  - recover more quickly, since the duration between I-frames is shorter

So, choosing a single fixed GOP for all frame rates is usually not optimal. A better approach is to choose a number that balances stream recovery time with the bitrate.

To explore the effects of choosing a GOP interval based on a fixed duration rather than a fixed number of frames, for some test groups, we dynamically selected a GOP interval such that the GOP would have a fixed duration in seconds. The GOP interval n for a desired duration d, for a given frame rate r can be calculated as $n = dr$. For example, for a GOP duration of 5 seconds, this results in the GOP intervals provided in Table 3.2.

Table 3.2: Correlation between frame rate and GOP interval for a GOP duration of 5 seconds

Frame Rate (kbps)	GOP Interval
1	5
2	10
5	25
15	75
30	150

Another common approach to GOP interval management is to use device-specific "dynamic GOP" features. When available, manufacturers typically claim that these features can lower stream bitrates without significantly impacting visual quality by dynamically determining efficient inclusion position of I-frames in the stream. When streams are less active, fewer I-frames will be included (resulting in a decreased bitrate). When streams are more active, more I-frames will be included (resulting in an increased bitrate).

We included examples of all these approaches (fixed, variable with frame rate, and dynamic) in the test scenarios to ascertain how they impact the stream.

TCP vs. UDP Streaming

Some project panel participants expressed interest in TCP streaming. While TCP is used widely in modern consumer-level streaming protocols such as HLS and DASH, it is generally not used for real-time video backhaul streaming unless it is required for network policy reasons (e.g., firewall configurations that will not allow UDP streaming). One of the primary reasons for this is that, with TCP, the transmitting host will make multiple attempts to deliver packets that are not acknowledged as having been received by the receiving host. While it is generally desirable to not lose stream packets, for real-time streams with small buffers, the retransmitted packet often doesn't arrive until the decoder has already advanced beyond the corresponding stream location. Rather than simply moving on, the decoder could wait for the retransmitted data, but this can stall out the stream, an outcome which is usually less desirable than the visual artifacts that result from simply continuing the decoding process while omitting the lost data. Alternatively, the decoder could employ larger buffers, but this increases stream latency, which is often undesirable for real-time surveillance video.

There are situations where, with certain network conditions and streaming configurations, selecting TCP may appear to provide superior results to UDP. However, this often means that the streaming configuration used was not a good match for the network conditions in the first place. In these cases, switching from UDP to TCP may seem to improve the stream, but often comes with other side effects such as progressive degradation or periodic skips.

Nevertheless, since there are scenarios for which TCP streaming may be useful, we included it in our test scenarios to make some observations on its impact on a stream.

Chapter 4:
Test Results and Analysis

Chapter 3 provides the test methodology, as well as important background information. The test results are presented in this chapter, with full presentation of stream quality analysis results provided in Appendix B.

Video Stream Testing

Axis Q8752-E

Baseline Test

The streaming configuration provided in Table 4.1 was selected for the Axis Q8752-E baseline test group (1,300 tests).

Table 4.1: Axis Q8752-E Baseline test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	ABR
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	Off

Although many encoders do not allow direct user control of a "compression level," the Axis Q8752-E does. A compression value of 30 was selected as it is the default, as well as the manufacturer-recommended value for general purpose streaming [4].

Figure 4.1 summarizes the results of the 1,300 tests conducted on the Axis Q8752-E with this (baseline) streaming configuration.

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	6 •	9 •	15 •••	17 •••	26 •	47 ••••	52 ••••	53 ••••	50 ••••	50 ••••	50 ••••	52 ••••	51 ••••
320x180 @ 2 FPS	9 •	12 •	18 ••	26 •••	37 •••	85 •••	77 ••••	89 ••••	90 ••••	85 ••••	86 ••••	82 ••••	89 ••••
320x180 @ 5 FPS	11 •	15 •	21 ••	23 •••	40 •••	89 •••	154 •••	164 ••••	160 ••••	153 ••••	133 ••••	165 ••••	149 ••••
320x180 @ 15 FPS	19 •	22 •	35 •	38 •	44 ••	80 •••	169 •••	295 •••	400 •••	422 ••••	373 ••••	424 ••••	407 ••••
320x180 @ 30 FPS	32 •	32 •	43 •	50 •	69 •	83 •••	152 •••	320 •••	409 •••	434 •••	614 ••••	661 ••••	695 ••••
480x270 @ 1 FPS	7 •	10 •	17 ••	20 ••	27 •••	51 ••	90 ••••	86 ••••	89 ••••	92 ••••	89 ••••	92 ••••	89 ••••
480x270 @ 2 FPS	10 •	14 •	24 ••	27 •	34 •••	77 •••	151 •••	159 ••••	156 ••••	147 ••••	138 ••••	150 ••••	155 ••••
480x270 @ 5 FPS	19 •	23 •	27 •	32 •	39 •••	89 •••	149 •••	275 •••	244 ••••	276 ••••	279 ••••	268 ••••	283 ••••
480x270 @ 15 FPS	37 •	37 •	41 •	45 •	64 •	87 •••	157 •••	325 •••	483 •••	531 •••	666 ••••	642 ••••	643 ••••
480x270 @ 30 FPS	58 •	58 •	60 •	63 •	79 •	137 •	151 •••	304 •••	431 •••	592 •••	1013 ••••	1062 ••••	1100 ••••
800x450 @ 1 FPS	20 •	20 •	21 •	25 •	34 ••	70 •••	146 •••	229 •••	264 ••••	274 ••••	259 ••••	260 ••••	244 ••••
800x450 @ 2 FPS	24 •	25 •	28 •	27 •	45 •	89 •••	156 •••	253 ••	331 •••	430 ••••	448 ••••	495 ••••	444 ••••
800x450 @ 5 FPS	56 •	54 •	54 •	63 •	61 •	96 •••	180 •••	369 •••	438 •••	664 •••	876 ••••	823 ••••	819 ••••
800x450 @ 15 FPS	103 •	106 •	102 •	103 •	100 •	124 •	197 •••	304 •••	504 •••	682 •••	1046 •••	2034 ••••	1747 ••••
800x450 @ 30 FPS	157 •	158 •	156 •	155 •	158 •	179 •	304 •	337 •••	449 •••	592 •••	1240 •••	2334 •••	3016 ••••
1280x720 @ 1 FPS	51 •	52 •	48 •	50 •	43 ••	77 ••	170 •••	223 •••	378 •••	589 •••	645 ••••	673 ••••	699 ••••
1280x720 @ 2 FPS	62 •	64 •	60 •	60 •	68 •	116 •	199 ••	311 •••	520 •••	626 •••	1090 •••	1314 ••••	1229 ••••
1280x720 @ 5 FPS	143 •	146 •	149 •	149 •	145 •	161 •	226 •••	370 •••	536 •••	691 •••	1080 •••	2323 •••	2489 ••••
1280x720 @ 15 FPS	280 •	293 •	296 •	294 •	276 •	295 •	319 ••	487 ••	512 •••	639 •••	1360 •••	2237 •••	4413 •••
1280x720 @ 30 FPS	388 •	409 •	411 •	388 •	393 •	398 •	405 •	638 •	857 ••	851 ••	1198 •••	2481 •••	5257 •••
1920x1080 @ 1 FPS	117 •	122 •	119 •	119 •	116 •	101 •	148 •••	315 •••	433 •••	545 ••••	869 •	1763 ••••	1790 ••••
1920x1080 @ 2 FPS	146 •	143 •	144 •	136 •	140 •	147 •	239 •	374 ••	403 •••	731 •••	1294 •••	2567 ••	3226 ••••
1920x1080 @ 5 FPS	323 •	328 •	338 •	347 •	333 •	340 •	349 •	480 ••	613 •••	719 •••	1472 •••	2582 •••	5908 •••
1920x1080 @ 15 FPS	738 •	719 •	721 •	735 •	735 •	736 •	660 •	739 •	835 •	1056 ••	1329 •••	2590 •••	5220 •••
1920x1080 @ 30 FPS	1047 •	1017 •	1049 •	1051 •	1049 •	1002 •	986 •	979 •	1094 •	1224 •	2022 ••	2472 •••	5160 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0, R_{targ}]$
R : $R \in (R_{targ}, R_{max}]$
R : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h264 main abr
GOP Mode: 30 f
Compression: 30
ZS Strength: off

Figure 4.1: Stream quality analysis for Axis Q8752-E Baseline test

As can be seen, acceptable target/maximum bitrate parameters can be found for nearly all of the resolutions and frame rates tested except for the some of the higher frame rates at the 1920x1080 resolution. This indicates that these cases may require either a more conservative target:maximum ratio, or may simply require a connection with a faster rate than was included in the testing.

MBR Rate Control

The purpose of this test group is to compare the performance of a basic MBR stream to the performance of the baseline (ABR) stream for the Axis Q8752-E. This test group consists of 1,300 tests and employed the streaming configuration of Table 4.2. Differences in configuration between this test group and that of the baseline test group are highlighted in bold, as in all following groups.

Table 4.2: Axis Q8752-E MBR test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	**MBR**
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	**N/A**
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	Off

Since MBR rate control is not as sophisticated as ABR, and since MBR implementations generally do not allow the specification of a target bitrate in addition to the maximum, it's not surprising for the MBR bitrate to be somewhat higher than a similarly configured ABR stream using the same maximum but with a lower target value also specified. This is what was observed in this test group. Bitrates for non-network-limited streams measured higher than those of the corresponding baseline (ABR) test streams for the majority of the streams in this test group.

Relative to the baseline test group, the following differences can be noted:

- The average bitrate for non-network-limited tests was 5.94% higher overall
- 1 FPS streams performed worse than those of other frame rates (14.09% higher bitrate than comparable tests in the baseline group)
- 30 FPS streams performed better than those of other frame rates (only 2.13% higher bitrate than comparable tests in the baseline group)
- Frame ratios were lower overall, indicating more frame loss (−2.74% for the 100% nominal rate tests, −2.52% for the 80% nominal rate tests, and −2.96% for the 50% nominal rate tests)

VBR Rate Control

VBR is essentially a "use as much data as you need" approach to bitrate management. It is typically used when visual quality is paramount and network capacity is sufficiently (and consistently) high. However, since neither condition is typically true for highway surveillance CCTVs (especially in rural areas), we limited testing of this mode to basic bitrate measurements.

This test group consists of 25 tests and employed the streaming configuration of Table 4.3.

Table 4.3: Axis Q8752-E VBR test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	**VBR**
Maximum Bitrate:	**N/A**
Target Bitrate:	**N/A**
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	Off

As can be seen in Table 4.4, bitrates for VBR streams can be quite high, especially at higher resolutions and frame rates.

Table 4.4: VBR test bitrates

Resolution and Frame Rate	Measured Average Bitrate (kbps)
320x180 @ 1 FPS	50
320x180 @ 2 FPS	92
320x180 @ 5 FPS	173

Resolution and Frame Rate	Measured Average Bitrate (kbps)
320x180 @ 15 FPS	424
320x180 @ 30 FPS	693
480x270 @ 1 FPS	93
480x270 @ 2 FPS	167
480x270 @ 5 FPS	291
480x270 @ 15 FPS	657
480x270 @ 30 FPS	1164
800x450 @ 1 FPS	271
800x450 @ 2 FPS	485
800x450 @ 5 FPS	882
800x450 @ 15 FPS	2016
800x450 @ 30 FPS	3528
1280x720 @ 1 FPS	705
1280x720 @ 2 FPS	1359
1280x720 @ 5 FPS	2595
1280x720 @ 15 FPS	5707
1280x720 @ 30 FPS	9005
1920x1080 @ 1 FPS	1949
1920x1080 @ 2 FPS	3706
1920x1080 @ 5 FPS	7844
1920x1080 @ 15 FPS	19991
1920x1080 @ 30 FPS	32228

Since VBR does not allow specification of a target bitrate, and since the bitrate of a VBR stream can vary wildly with changes in the scene, the "frame ratio" analysis (which explores how frame receipt is affected when a link's capacity drops below its nominal rate) isn't especially useful for VBR.

H.264 High Profile

The purpose of this test group is to compare the performance of a stream using the H.264 "High" profile to the performance of the baseline stream (which uses the H.264 "Main" profile) for the Axis Q8752-E.

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.5.

Table 4.5: Axis Q8752-E H.264 High test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**H.264 (High)**
Bitrate Control Mode:	ABR
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	Off

Performance results for this configuration were not dramatically different from those of the baseline test group. However, relative to the baseline test group, the following differences can be noted:

- The average bitrate for non-network-limited tests was roughly equivalent (1.10% higher)
- Bitrates tended to be lower for the lower resolutions (averaging −4.92% for 320x180, and −1.05% for 480x270) and higher for the higher resolutions (averaging +2.70% for 800x450, +3.32% for 1280x720, and +5.47% for 1920x1080)

- Bitrates tended to be lower for the lower frame rates (averaging −0.55% for 1 FPS, −1.66% for 2 FPS, and −1.27% for 5 FPS) and higher for the higher frame rates (averaging +4.27% for 15 FPS, and +4.73% for 30 FPS)
- Frame ratio averages were nearly identical (−0.06% for the 50% nominal rate tests, −0.16% for the 80% nominal rate tests, and −0.53% for the 100% nominal rate tests)

H.265 Main Profile

The purpose of this test group is to compare the performance of a stream using H.265 (with the "Main" profile) to the performance of the baseline stream, which uses H.264 (with the "Main" profile) for the Axis Q8752-E.

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.6.

Table 4.6: Axis Q8752-E H.265 Main test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**H.265 (Main)**
Bitrate Control Mode:	ABR
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	Off

Performance results for this H.265 configuration were significantly better than those of the baseline test group. Relative to the baseline test group, the following differences can be noted:

- The average bitrate for non-network-limited tests was 9.88% lower overall

- Average bitrates were lower across all resolutions (−11.06% for 320x180, −8.26% for 480x270, −9.99% for 800x450, −11.66% for 1280x720, and −8.43% for 1920x1080)
- Average bitrates were lower across all frame rates (−6.52% for 1 FPS, −13.17% for 2 FPS, −12.10% for 5 FPS, −10.02% for 15 FPS, and −7.58% for 30 FPS)
- Frame ratios were slightly better overall (+1.62% for the 50% nominal rate tests, +1.50% for the 80% nominal rate tests, and +0.21% for the 100% nominal rate tests)

M-JPEG

This test group consists of 25 tests and employed the streaming configuration of Table 4.7.

Table 4.7: Axis Q8752-E M-JPEG test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**M-JPEG**
Bitrate Control Mode:	**N/A**
Maximum Bitrate:	**N/A**
Target Bitrate:	**N/A**
GOP Interval:	**N/A**
Frame Rate Mode:	**N/A**
Compression Level:	30
Zipstream Strength:	**N/A**

As seen in Table 4.7, bitrates for M-JPEG streams can be very high. Relative to the baseline test group, the following differences can be noted:

- The average bitrates for non-network-limited tests were orders of magnitude higher

As seen in Figure 4.2, bitrates for M-JPEG streams can be very high. Relative to the baseline test group, the following differences can be noted:

- The average bitrates for non-network-limited tests were orders of magnitude higher.
- Frame delivery was very poor for our 1920x1080 tests, but the cause has not been determined.

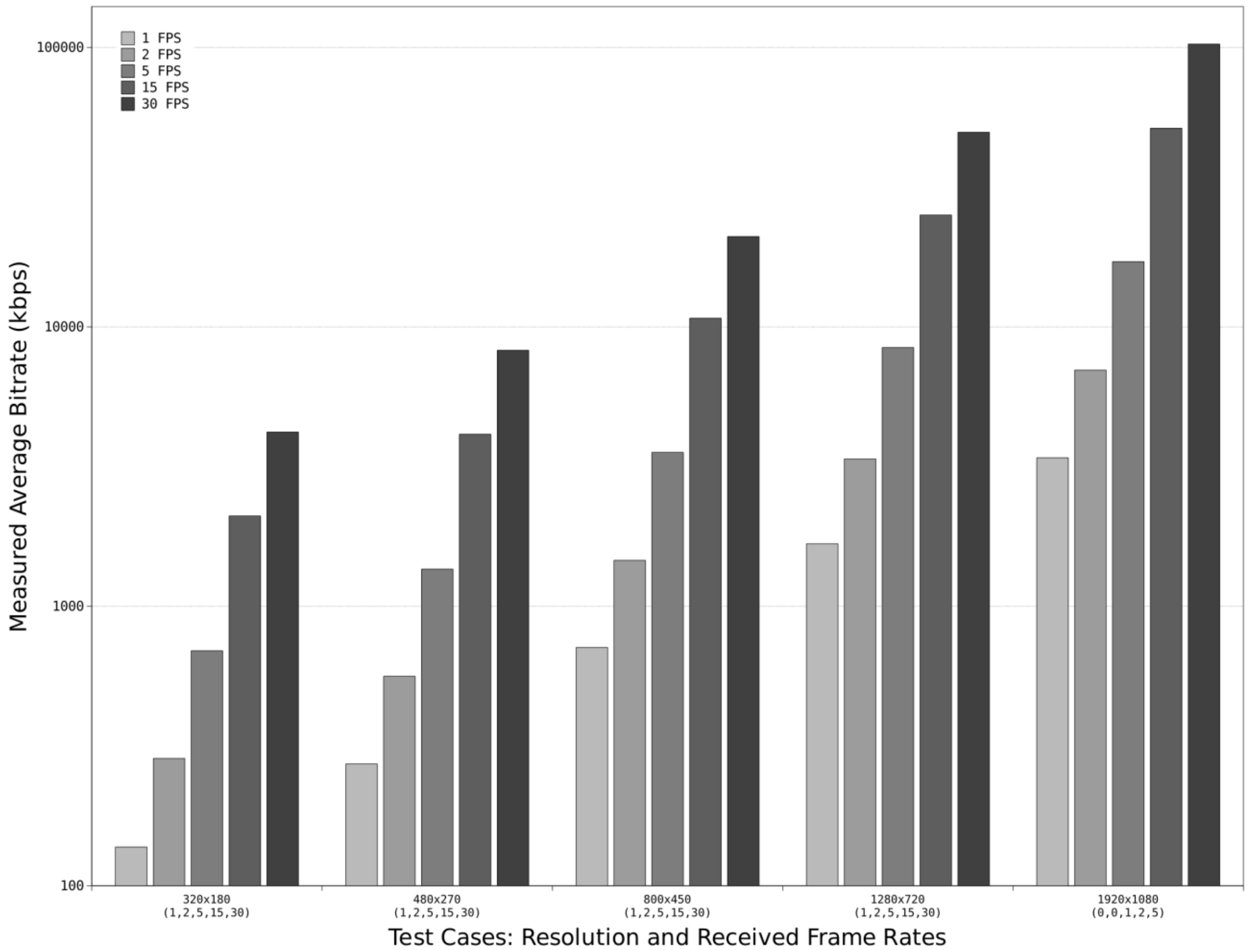

Figure 4.2: Average bitrates for Axis Q8752-E M-JPEG test

Varying GOP Interval with Frame Rate

To explore the effects of choosing a GOP interval based on a fixed duration rather than a fixed number of frames, for each test in this test group, we dynamically selected a GOP interval such that the GOP would have a duration of 5 seconds, as shown in Table 4.8.

Table 4.8: Correlation between frame rate and GOP interval for a GOP duration of 5 seconds

Frame Rate (kbps)	GOP Interval
1	5
2	10
5	25
15	75
30	150

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.9.

Table 4.9: Axis Q8752-E Varying GOP Interval test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	ABR
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Interval:	**fixed, *5r* frames**
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	Off

As expected, the performance of this test group (relative to the baseline test group which uses a GOP interval of 30 for all tests), depends on frame rate. The key findings are as follows:

For the 1, 2, and 5 FPS tests, for which the GOP interval values were lower than the baseline group's value of 30, I-frames comprised a larger portion of the stream and higher average bitrates were observed (+36.97%, +16.26%, and +0.59% respectively).

For the 15 and 30 FPS tests, for which the GOP interval values were higher than the baseline group's value of 30, I-frames comprised a smaller portion of the stream and lower average bitrates were observed (−6.27% and −9.55% respectively).

Compression 100

While not all encoders allow direct user control of a "compression" parameter, many Axis devices such as the Axis Q8752-E do. Although "compression" parameters are not always comparable across devices, it defaults to a value of 30 on the Axis Q8752-E, which is also the value recommended by Axis [4].

The purpose of this test group is to explore the magnitude of bitrate reduction possible for the (reasonably active) test scene. Through experimentation it was discovered that, even at a compression value of 100, the stream continued to provide a very useable facsimile of the test scene. Since this may be sufficient for some rural sites with extremely limited network connectivity, it was decided to use a compression value of 100 for this test group. This allows the results of this test group to provide a general idea of how much bitrate reduction is possible through use of the compression parameter, while still retaining a useable stream. If higher visual quality is desired, it can be obtained (at the cost of bitrate) by lowering the value of the compression parameter.

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.10.

Notable results compared to the baseline (compression 30) test group:

- Bitrates were dramatically reduced in nearly all non-network-limited tests, with an average bitrate reduction of 57.77%
- Frame ratios were also improved for the majority of network-limited tests, averaging +17.61% for the 50% nominal rate tests, +12.05% for the 80% nominal rate tests, and +10.40% for the 100% nominal rate tests

Table 4.10: Axis Q8752-E Compression 100 test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	ABR
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	**100**
Zipstream Strength:	Off

Zipstream

Zipstream is a set of Axis-proprietary video encoding enhancements which can be used in conjunction with H.264, H.265, and other stream encodings. Axis recommends its use [4] and describes it as "radically more efficient than standard encoders" [5].

The main parameter specifying the behavior of Zipstream is the "Zipstream strength" parameter. Possible values for this parameter are 10 (default), 20, 30, 40, 50, and "off." Higher values tend to reduce the bitrate at the expense of visual quality, although Zipstream claims to prioritize the retention of important visual details over those of less importance [4]. Axis warns that some clients/decoders may not be compatible with Zipstream levels higher than 10 [4].

Axis describes the Zipstream strength levels as in Table 4.11 [5].

Table 4.11: Zipstream strength levels

Strength	Effort Level	Visible Consequences
Off	Off	None
10	Low	No visible effect in most scenes

Strength	Effort Level	Visible Consequences
20	Medium	Visible effect in some scenes: less noise, and slightly lower level of detail in regions of lower interest
30	High	Visible effect in many scenes: less noise, and lower level of detail in regions of lower interest
40	Higher	Visible effect in even more scenes: less noise, and lower level of detail in regions of lower interest
50	Extreme	Visible effect in most scenes: less noise, and lower level of detail in regions of lower interest

Zipstream Strength 10

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.12.

Table 4.12: Axis Q8752-E Zipstream Strength 10 test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	ABR
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	**10**

Notable results compared to the baseline (Zipstream off) test group:

- Bitrates were reduced in most non-network-limited configurations, with an average bitrate reduction of 11.12%

- Frame ratios for network-limited tests were slightly improved, averaging +2.99% for the 50% nominal rate tests, +0.98% for the 80% nominal rate tests, and +1.79% for the 100% nominal rate tests

Zipstream Strength 30

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.13.

Table 4.13: Axis Q8752-E Zipstream Strength 30 test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	ABR
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	**30**

Notable results compared to the baseline (Zipstream off) test group:

- Bitrates were reduced in most non-network-limited configurations, with an average bitrate reduction of 15.61%
- Frame ratios for network-limited tests were slightly improved, averaging +2.86% for the 50% nominal rate tests, +0.42% for the 80% nominal rate tests, and +0.08% for the 100% nominal rate tests

Zipstream Strength 50

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.14.

Table 4.14: Axis Q8752-E Zipstream Strength 50 test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	ABR
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	**50**

Notable results compared to the baseline (Zipstream off) test group:

- Bitrates were reduced in most non-network-limited configurations, however for many test cases in which the specified target and maximum bitrates were at the low end of the range of realistic values (especially those with lower frame rates), bitrates were dramatically higher. The reasons for this are unclear. However, for nearly every test case configuration with sufficiently high specified target and maximum bitrate values, bitrate reduction was considerable.
- Frame ratios for network-limited tests were mixed, likely due to the aforementioned phenomenon

Zipstream Strength 30 with Dynamic GOP Interval

Zipstream features an optional "dynamic GOP" mode which Axis recommends using whenever Zipstream strength is 30 or higher [4]. Axis describes this mode as a way to remove "unnecessary" I-frames from the stream for bitrate reduction purposes [4]. With the dynamic GOP mode, shorter GOP intervals (more I-frames) will be used for more active scenes, and longer GOP intervals (fewer I-frames) will be used for less active scenes. Minimum and maximum values are specified by the user in order to restrict the GOP intervals to a desired range.

This test group consists of 1,300 tests and employed a streaming configuration identical to that of the Zipstream Strength 30 tests (Table 4.14), except that the GOP mode is dynamic, constrained to a range of 1-300 frames.

Analysis of results for the non-network-limited tests in this test group are provided in Table 4.15.

Table 4.15: GOP and bitrate statistics for Dynamic GOP test

Frame Rate	Average GOP Interval	Average GOP Duration	Average Bitrate Relative to Corresponding Non-Dynamic-GOP Zipstream Strength 30 Tests
1	2.4	2.4	167.18%
2	4.6	2.3	139.40%
5	23.4	4.7	101.47%
15	64.8	4.3	85.44%
30	64.3	2.1	85.97%

As expected, the test cases with an average GOP interval longer than the GOP interval (30) of the corresponding tests from the non-dynamic-GOP Zipstream Strength 30 group tended to have lower relative bitrates, and those with longer GOP intervals had higher relative bitrates.

Selection of a higher minimum GOP interval value (e.g., 30) could prevent the higher relative bitrates observed for frame rates 1, 2, and 5 FPS. However, this would come at the cost of stream recovery time, so careful selection of the minimum and maximum GOP interval values is recommended, especially in cases where network quality is low and likelihood of stream corruption is high.

To summarize, the Zipstream dynamic GOP mode, together with a carefully chosen interval range, can result in lower bitrates at the cost of higher stream recovery times. It is a feature worth considering, especially in situations where the following apply:

- The clients/decoders are known to be compatible
- Zipstream strength is set to 30 or higher
- The network is relatively reliable
- Scenes are not extremely active

TCP Streaming

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.16.

Table 4.16: Axis Q8752-E TCP Streaming test streaming configuration

Item	Config
Stream Transport:	***RTP (TCP)***
Encoding:	H.264 (Main)
Bitrate Control Mode:	ABR
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Frame Rate Mode:	fixed
Compression Level:	30
Zipstream Strength:	Off

Notable results compared to the baseline (UDP) test group:

- Bitrates increased for nearly all non-network-limited tests, averaging 5.60% higher
- Frame ratios were slightly lower overall, averaging +0.38% for the 50% nominal rate tests, −0.99% for the 80% nominal rate tests, and −1.55% for the 100% nominal rate tests. TCP did not result in superior frame delivery in the presence of network constraints.

These results are consistent with expectations, given the additional overhead of TCP.

Bosch MIC inteox 7100i

Baseline Test

The streaming configuration provided in Table 4.17 was selected for the Bosch MIC inteox 7100i baseline test group.

Table 4.17: Bosch MIC inteox 7100i Baseline test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (High)
Bitrate Control Mode:	ABR-like
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Mode:	IBP
GOP Interval:	fixed, 30 frames

Since this device (with the firmware version tested) does not appear to support the Main profile of H.264, we used the High profile for the baseline configuration.

Also, Bosch does not appear to identify or name this device's bitrate control mechanism. However, it allows the specification of a target bitrate and a maximum bitrate, hence we refer to it here as "ABR-like."

Figure 4.3 summarizes the results of the 1,040 tests conducted on the Bosch MIC inteox 7100i with this (baseline) streaming configuration.

As can be seen, the majority of the tests performed poorly, both in terms of bitrate as well as frame loss. The primary reason for this is that, even when the target/maximum bitrate parameters are well within practical ranges for a given stream configuration, the resulting average bitrate was consistently higher than the specified values. This is discussed further in Chapter 5.

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
512x288 @ 1 FPS	5 •	17 •	29 •	31 ••	54 •	123 •••	275 •	654 •	717 •	789 ••	823 ••••	826 ••••	830 ••••
512x288 @ 2 FPS	11 •	15 •	30 •	34 ••	48 ••	107 ••	204 ••	434 ••	659 ••	857 ••	1783 ••	1723 ••••	1807 ••••
512x288 @ 5 FPS	22 •	22 •	33 •	36 •	53 ••	111 ••	221 •••	436 •••	642 •••	847 •••	1677 •••	3311 •••	4180 ••••
512x288 @ 15 FPS	57 •	58 •	58 •	57 •	71 •	130 ••	231 ••	442 ••	649 •••	844 •••	1675 •••	3300 •••	6608 •••
512x288 @ 30 FPS	105 •	102 •	101 •	106 •	106 •	156 •	257 ••	466 ••	679 ••	866 ••	1684 •••	3339 •••	6605 •••
768x432 @ 1 FPS	11 •	10 •	29 •	31 •	46 ••	104 •	239 ••	618 •	1048 •	1231 •	1685 ••	1766 ••••	1782 ••••
768x432 @ 2 FPS	21 •	21 •	26 •	31 •	51 ••	117 ••	206 ••	702 ••	623 ••	834 ••	1655 ••	3791 ••	3861 ••••
768x432 @ 5 FPS	44 •	45 •	43 •	45 •	57 •	108 ••	208 •••	436 •••	638 •••	817 •••	1666 •••	3350 •••	6588 ••
768x432 @ 15 FPS	118 •	116 •	147 •	113 •	115 •	135 ••	230 ••	432 ••	652 ••	843 •••	1648 •••	3311 •••	6636 •••
768x432 @ 30 FPS	210 •	202 •	210 •	287 •	204 •	209 •	262 ••	478 ••	667 ••	863 ••	1679 •••	3373 •••	6628 •••
1280x720 @ 1 FPS	22 •	22 •	26 •	22 •	25 •	120 ••	157 •	510 •••	887 •	1301 •	2439 •	3524 •	4284 •••
1280x720 @ 2 FPS	48 •	47 •	60 •	47 •	51 •	115 ••	226 ••	431 ••	650 ••	809 ••	1603 ••	3467 ••	6967 ••
1280x720 @ 5 FPS	99 •	95 •	97 •	96 •	97 •	123 ••	209 ••	408 •••	617 •••	807 •••	1682 •••	3356 •••	6571 •••
1280x720 @ 15 FPS	241 •	247 •	234 •	249 •	249 •	246 •	265 ••	456 ••	642 ••	830 •••	1665 •••	3281 •••	6655 •••
1280x720 @ 30 FPS	417 •	441 •	440 •	446 •	441 •	447 •	443 •	493 ••	711 ••	891 ••	1714 •••	3296 •••	6646 •••
1920x1080 @ 1 FPS	48 •	57 •	46 •	49 •	52 •	114 ••	234 ••	401 ••	557 ••	897 •	2244 •	4941 •	6733 •
1920x1080 @ 2 FPS	98 •	101 •	102 •	99 •	133 •	106 ••	232 ••	435 •••	581 ••	825 ••	1517 ••	3059 ••	7340 •
1920x1080 @ 5 FPS	201 •	205 •	196 •	202 •	203 •	205 •	241 ••	438 ••	606 •••	839 •••	1619 •••	3230 •••	6569 ••
1920x1080 @ 15 FPS	492 •	509 •	515 •	518 •	522 •	490 •	506 •	474 ••	663 •••	843 •••	1615 •••	3298 •••	6531 •••
1920x1080 @ 30 FPS	912 •	853 •	917 •	900 •	867 •	1105 •	929 •	902 •	826 •	967 ••	1643 •••	3391 •••	6706 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0, R_{targ}]$
R : $R \in (R_{targ}, R_{max}]$
R : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Bosch 7100i
Scene: scene1
Encoding: H.264
Frame Mode: IBP
GOP Mode: 30 f

Figure 4.3: Stream quality analysis for Bosch MIC inteox 7100i Baseline test

H.265 Main Profile

The purpose of this test group is to compare the performance of a stream using H.265 (with the "Main" profile) to the performance of the baseline stream, which uses H.264 (with the "High" profile) for the Bosch MIC inteox 7100i.

This test group consists of 1,040 tests and employed the streaming configuration of Table 4.18.

Table 4.18: Bosch MIC inteox 7100i H.265 Main test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**H.265 (Main)**
Bitrate Control Mode:	ABR-like
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate

Item	Config
GOP Mode:	IBP
GOP Interval:	fixed, 30 frames

Performance results for this H.265 configuration were significantly better than those of the baseline test group. Relative to the baseline test group, the following differences can be noted:

- The average bitrate for non-network-limited tests was 14.44% lower overall
- Average bitrates were lower across all resolutions (−4.78% for 512x288, −11.40% for 768x432, −17.41% for 1280x720, and −24.16% for 1920x1080)
- Average bitrates were lower across all frame rates (−10.91% for 1 FPS, −7.03% for 2 FPS, −12.79% for 5 FPS, −18.81% for 15 FPS, and −22.64% for 30 FPS)
- Frame ratios were better overall (+10.29% for the 50% nominal rate tests, +7.52% for the 80% nominal rate tests, and +7.29% for the 100% nominal rate tests)

M-JPEG

This test group consists of 260 tests and employed the streaming configuration of Table 4.19.

Table 4.19: Bosch MIC inteox 7100i M-JPEG test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**M-JPEG**
Bitrate Control Mode:	ABR-like
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	**N/A**
GOP Mode:	**N/A**
GOP Interval:	**N/A**

Unlike the other devices tested in this study, the primary Bosch MIC inteox 7100i M-JPEG streaming mode is based on the specification of a desired maximum bitrate, rather than a desired JPEG quality or compression value.

We performed a series of M-JPEG streaming tests for each of the link classes. For all tests in each class, we specified a maximum bitrate (R_{max}) of 80% of the class's nominal rate (Table 4.20).

Table 4.20: Specified maximum bitrates (R_{max}) for M-JPEG tests by link class

Link Class	Typical Use	Nominal Rate (kbps)	R_{max} (kbps)
1	POTS Modem	9.6	7
2	POTS Modem	14.4	11
3	POTS Modem	28.8	23
4	POTS Modem	33.6	26
5	POTS Modem	56	44
6	ISDN BRI	128	102
7	2G	256	204
8	DSL, 3G	512	409
9	DSL, 3G	768	614
10	cable, 4G, 5G, Ethernet, µwave	1000	800
11	cable, 4G, 5G, Ethernet, µwave	2000	1600
12	cable, 4G, 5G, Ethernet, µwave	4000	3200
13	cable, 4G, 5G, Ethernet, µwave	8000	6400

The test results are summarized in Figure 4.4. As with this device's H.264 and H.265 streaming modes, the specified maximum bitrate appears to be treated as a suggestion rather than as a strict limit (R_{max} is represented by the dashed boxes in the figure). Speculating from the results, it appears that the device may internally determine its own minimum quality or bitrate limit and not allow this limit to be undershot. Therefore, it's worth noting that the resulting stream may exceed the specified maximum bitrate by up to several orders of magnitude.

In contrast to the M-JPEG test results for the other devices in this study, no frame loss was detected for any of the M-JPEG tests we performed on this device.

Relative to the baseline test group, the following differences can be noted:

- The average bitrates for non-network-limited tests were significantly higher.

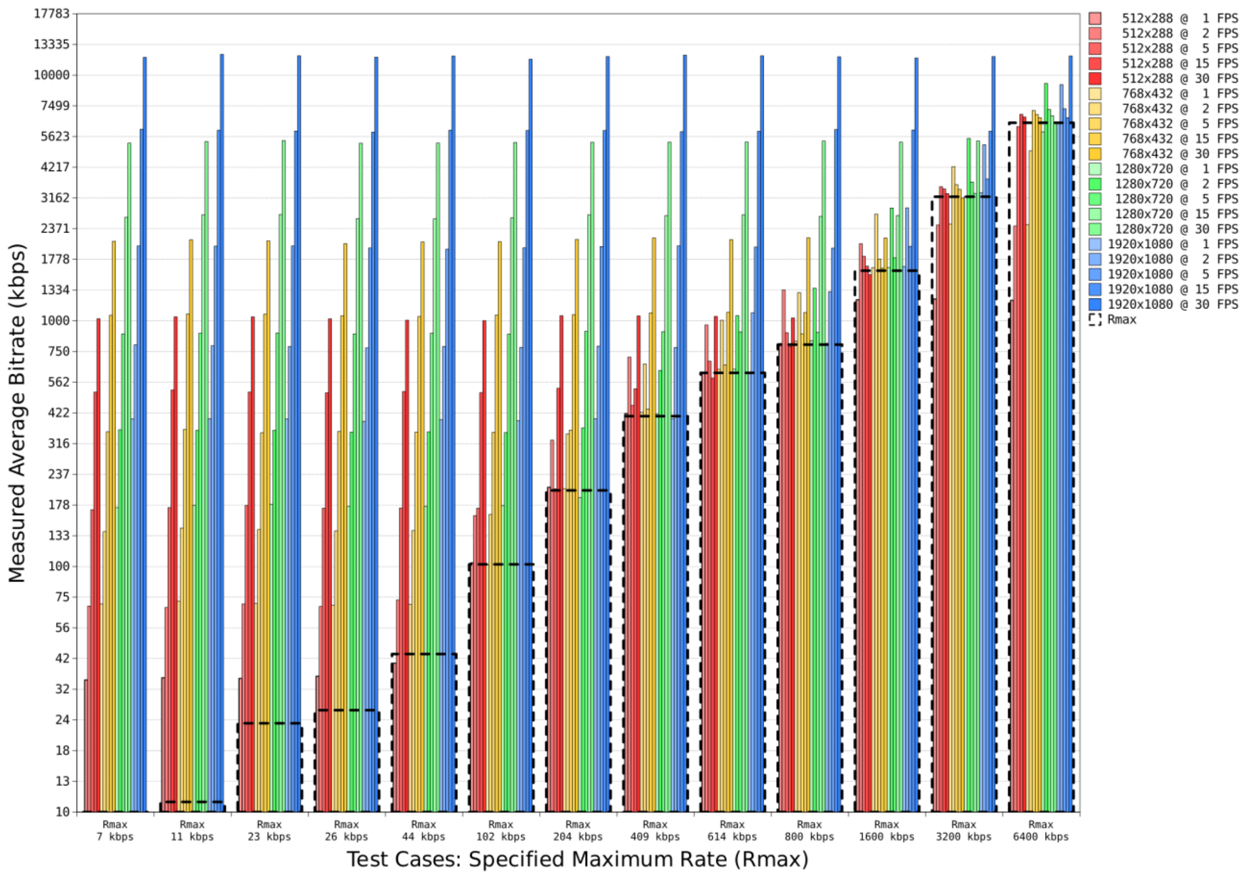

Figure 4.4: Average bitrates for Bosch MIC inteox 7100i M-JPEG test

Varying GOP Interval with Frame Rate

To explore the effects of choosing a GOP interval based on a fixed duration rather than a fixed number of frames, for each test in this test group, we dynamically selected a GOP interval such that the GOP would have a duration of 5 seconds:

Table 4.20: Correlation between frame rate and GOP interval for a GOP duration of 5 seconds

Frame Rate (kbps)	GOP Interval
1	5
2	10
5	25
15	75
30	150

This test group consists of 1,040 tests and employed the streaming configuration of Table 4.21.

Table 4.21: Bosch MIC inteox 7100i Varying GOP Interval test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (High)
Bitrate Control Mode:	ABR-like
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Mode:	IBP
GOP Interval:	**fixed, 5*r* frames**

As expected, the performance of this test group (relative to the baseline test group which uses a GOP interval of 30 for all tests), depends on frame rate. The key findings are as follows:

- For the 1, 2, and 5 FPS tests, for which the GOP interval values were lower than the baseline group's value of 30, I-frames comprised a larger portion of the stream and slightly higher (but mixed) average bitrates were observed (+4.21%, −2.59%, and +1.46% respectively).

- For the 15 and 30 FPS tests, for which the GOP interval values were higher than the baseline group's value of 30, I-frames comprised a smaller portion of the stream and slightly lower average bitrates were observed (−1.44% and −3.98% respectively).

Dynamic GOP Interval

The Bosch MIC inteox 7100i features an optional dynamic GOP mode (referred to as "auto I-frame distance") that automatically manages the GOP interval of a stream.

We tested this configuration with a test group consisting of 1,040 tests and employing the streaming configuration of Table 4.22.

Table 4.22: Bosch MIC inteox 7100i Dynamic GOP Interval test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (High)
Bitrate Control Mode:	ABR-like
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Mode:	IBP
GOP Interval:	**dynamic**

Analysis of results for the non-network-limited tests in this test group are provided in Table 4.23.

Average bitrates in these results do not correlate as expected with the average GOP intervals. This is possibly due to the device's apparent difficulty keeping stream bitrates in the range of the specified target and maximum values. Frame ratios were largely unchanged

Table 4.23: GOP and bitrate statistics for Dynamic GOP test

Frame Rate	Average GOP Interval	Average GOP Duration	Average Bitrate Relative to Corresponding Baseline Tests
1	2.5	2.5	−0.94%
2	5.0	2.5	−1.94%
5	12.5	2.5	−2.67%
15	181.7	12.1	−2.43%
30	217.3	7.2	−4.23%

TCP Streaming

This test group consists of 1,040 tests and employed the streaming configuration of Table 4.24.

Table 4.24: Bosch MIC inteox 7100i TCP Streaming test streaming configuration

Item	Config
Stream Transport:	***RTP (TCP)***
Encoding:	H.264 (High)
Bitrate Control Mode:	ABR-like
Maximum Bitrate:	80% of nominal rate
Target Bitrate:	80% of maximum rate
GOP Mode:	IBP
GOP Interval:	fixed, 30 frames

Compared to the baseline (UDP) test group:

- Bitrates increased for nearly all non-network-limited tests, averaging 4.53% higher
- Frame ratio results were mixed, averaging +3.74% for the 50% nominal rate tests, −0.38% for the 80% nominal rate tests, and +0.17% for the 100% nominal rate tests

These results are consistent with expectations, given the additional overhead of TCP.

CostarHD RISE 4260HD

Baseline Test

The streaming configuration provided in Table 4.25 was selected for the CostarHD RISE 4260HD baseline test group.

Table 4.25: CostarHD RISE 4260HD Baseline test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	CBR
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Constrained Mode:	off

Since this device (with the firmware version we tested) does not support ABR, we selected CBR for its baseline configuration. In addition, this device did not allow the specification of CBR target bitrates below 256 kbps, so we omitted tests involving link classes with nominal rates below 512 kbps (which is the lowest link class for which the target rate would be within the device's allowed range).

Figure 4.5 summarizes the results of the 480 tests conducted on the CostarHD RISE 4260HD with this (baseline) streaming configuration.

As can be seen, measured average bitrates for the non-network-limited tests often marginally exceeded the specified target bitrates, especially for higher-frame-rate configurations. Only one case — the least reasonable of the entire test group — exceeded the specified maximum bitrate.

	R_{nom}, R_{targ} (kbps)					
	512	768	1000	2000	4000	8000
	327	491	640	1280	2560	5120
352x240 @ 1 FPS	243 •••	241 ••••	238 ••••	254 ••••	256 ••••	240 ••••
352x240 @ 2 FPS	340 •••	447 •••	426 ••••	414 ••••	422 ••••	431 ••••
352x240 @ 5 FPS	340 •••	512 •••	673 •••	886 ••••	877 ••••	890 ••••
352x240 @ 15 FPS	344 •••	517 •••	673 •••	1344 •••	2223 •••	2220 ••••
352x240 @ 30 FPS	347 •••	523 •••	677 •••	1348 •••	2717 •••	4057 •••
720x480 @ 1 FPS	325 •••	495 •••	690 •••	1046 •••	1034 ••••	1086 ••••
720x480 @ 2 FPS	287 •••	437 •••	616 •••	1334 •••	1901 ••••	1824 ••••
720x480 @ 5 FPS	318 •••	465 •••	611 •••	1330 •••	2709 •••	4011 ••••
720x480 @ 15 FPS	355 •••	530 •••	688 •••	1365 •••	2719 •••	5384 •••
720x480 @ 30 FPS	354 •••	518 •••	674 •••	1363 •••	2691 •••	5433 •••
1280x720 @ 1 FPS	327 •••	491 •••	622 •••	1300 •••	2587 •••	2595 ••••
1280x720 @ 2 FPS	290 •••	442 •••	554 •••	1126 •••	2640 •••	4584 •••
1280x720 @ 5 FPS	332 •••	473 •••	598 •••	1152 •••	2600 •••	5367 •••
1280x720 @ 15 FPS	354 •••	529 •••	662 •••	1375 •••	2679 •••	5429 •••
1280x720 @ 30 FPS	350 •••	517 •••	675 •••	1344 •••	2719 •••	5420 •••
1920x1080 @ 1 FPS	324 •••	476 •••	594 •••	1265 •••	2595 •••	5383 •••
1920x1080 @ 2 FPS	288 •••	429 •••	562 •••	1139 •••	2268 •••	5420 •••
1920x1080 @ 5 FPS	328 •••	498 •••	620 •••	1174 •••	2240 •••	5204 •••
1920x1080 @ 15 FPS	381 •••	528 •••	663 •••	1330 •••	2731 •••	5366 •••
1920x1080 @ 30 FPS	529 •	586 •••	669 •••	1367 •••	2682 •••	5423 •••

R	:	measured average bitrate (kbps)
R_{nom}	:	nominal bitrate for link class (kbps)
R_{100}	:	net-limit test rate (100% of R_{nom})
R_{80}	:	net-limit test rate (80% of R_{nom})
R_{50}	:	net-limit test rate (50% of R_{nom})
R_{max}	:	specified max. rate (80% of R_{nom})
R_{targ}	:	specified target rate (80% of R_{max})
F_r	:	# frames received
F_e	:	# frames expected

R (green)	:	$R \in [0, R_{targ}]$
R (yellow)	:	$R \in (t, 1.25t]$
R (red)	:	$R \in (1.25t, \infty)$
••••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	:	$F_r \div F_e \geq 90\%$ for R_{100}
•	:	$F_r \div F_e \geq 90\%$ for no test rates

Device:	Cohu 4261
Scene:	scene1
Encoding:	H264 Main CBR
GOP Mode:	30 f
Constrained:	Off

Figure 4.5: Stream quality analysis for CostarHD RISE 4260HD Baseline test

H.264 High Profile

The purpose of this test group is to compare the performance of a stream using the H.264 "High" profile to the performance of the baseline stream (which uses the H.264 "Main" profile) for the CostarHD RISE 4260HD.

This test group consists of 480 tests and employed the streaming configuration of Table 4.26.

Table 4.26: CostarHD RISE 4260HD H.264 High test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**H.264 (High)**
Bitrate Control Mode:	CBR
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Constrained Mode:	off

Compared to the baseline (H.264 Main) test group:

- Bitrates were nearly identical, averaging +0.64% higher
- Frame ratio results were nearly identical

Varying GOP Interval with Frame Rate

To explore the effects of choosing a GOP interval based on a fixed duration rather than a fixed number of frames, for each test in this test group, we dynamically selected a GOP interval such that the GOP would have a duration of 5 seconds, as shown in Table 4.27.

Table 4.27: Correlation between frame rate and GOP interval for a GOP duration of 5 seconds

Frame Rate (kbps)	GOP Interval
1	5
2	10
5	25
15	75
30	150

This test group consists of 480 tests and employed the streaming configuration of Table 4.28.

Table 4.28: CostarHD RISE 4260HD Varying GOP Interval test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	CBR
Target Bitrate:	80% × 80% of nominal rate
GOP Interval:	**fixed, 5*r* frames**
Constrained Mode:	off

As expected, the performance of this test group (relative to the baseline test group which uses a GOP interval of 30 for all tests), depends on frame rate. The key findings are as follows:

- For the 1, 2, and 5 FPS tests, for which the GOP interval values were lower than the baseline group's value of 30, I-frames comprised a larger portion of the stream and higher average bitrates were observed (+5.47%, +5.99%, and +2.24% respectively).
- For the 15 and 30 FPS tests, for which the GOP interval values were higher than the baseline group's value of 30, I-frames comprised a smaller portion of the stream and lower average bitrates were observed (−0.75% and −1.63% respectively)

Constrained Mode

This device has a feature called "Video Constrained Mode" which is recommended by the manufacturer for use over cellular networks [6]. We were unable to find much documentation about this function, nor were we able to infer how it functions.[5] Nevertheless, we included it in our testing and summarize the results here.

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[5] During our research, we came across one piece of literature that alluded to this feature having something to do with adherence to a specified maximum bitrate (Rmax). However, the device we tested would only allow a maximum bitrate to be specified in VBR mode, and Video Constrained mode could only be enabled in CBR mode. Thus, there was no way for us to simultaneously specify both Video Constrained Mode and a maximum bitrate.

This test group consists of 480 tests and employed the streaming configuration of Table 4.29.

Table 4.29: CostarHD RISE 4260HD Constrained Mode test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	CBR
Target Bitrate:	80% × 80% of nominal rate
GOP Interval:	fixed, 30 frames
Constrained Mode:	**on**

Compared to the baseline test group (for which "Video Constrained Mode" was disabled):

- Bitrates were nearly identical, averaging +0.19% higher
- Frame ratio results were very modestly improved, averaging +0.21% for the 50% nominal rate tests, +0.87% for the 80% nominal rate tests, and +0.58% for the 100% nominal rate tests

From our test results it is difficult to discern any substantial differences resulting from the use of the "Video Constrained Mode" feature. Frame delivery was very slightly improved, which likely accounts for the very slightly higher bitrate averages, but these numbers are all small enough that they likely would not withstand repeated testing.

M-JPEG

This test group consists of 60 tests and employed the streaming configuration of Table 4.30.

Three M-JPEG quality levels were chosen for testing: 30, 75, and 100. The test results are summarized in Figure 4.6. Relative to the baseline test group, the following differences can be noted:

- The average bitrates for non-network-limited tests were significantly higher when resolution and/or frame rate was high.

- Frame delivery suffered at higher frame rates for high-resolution scenarios. Speculating from the test results, this could be due to a throughput ceiling (of roughly 10 Mbps) intrinsic to this device.

Table 4.30: CostarHD RISE 4260HD M-JPEG test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**M-JPEG**
Bitrate Control Mode:	**N/A**
Target Bitrate:	**N/A**
GOP Interval:	**N/A**
Constrained Mode:	off

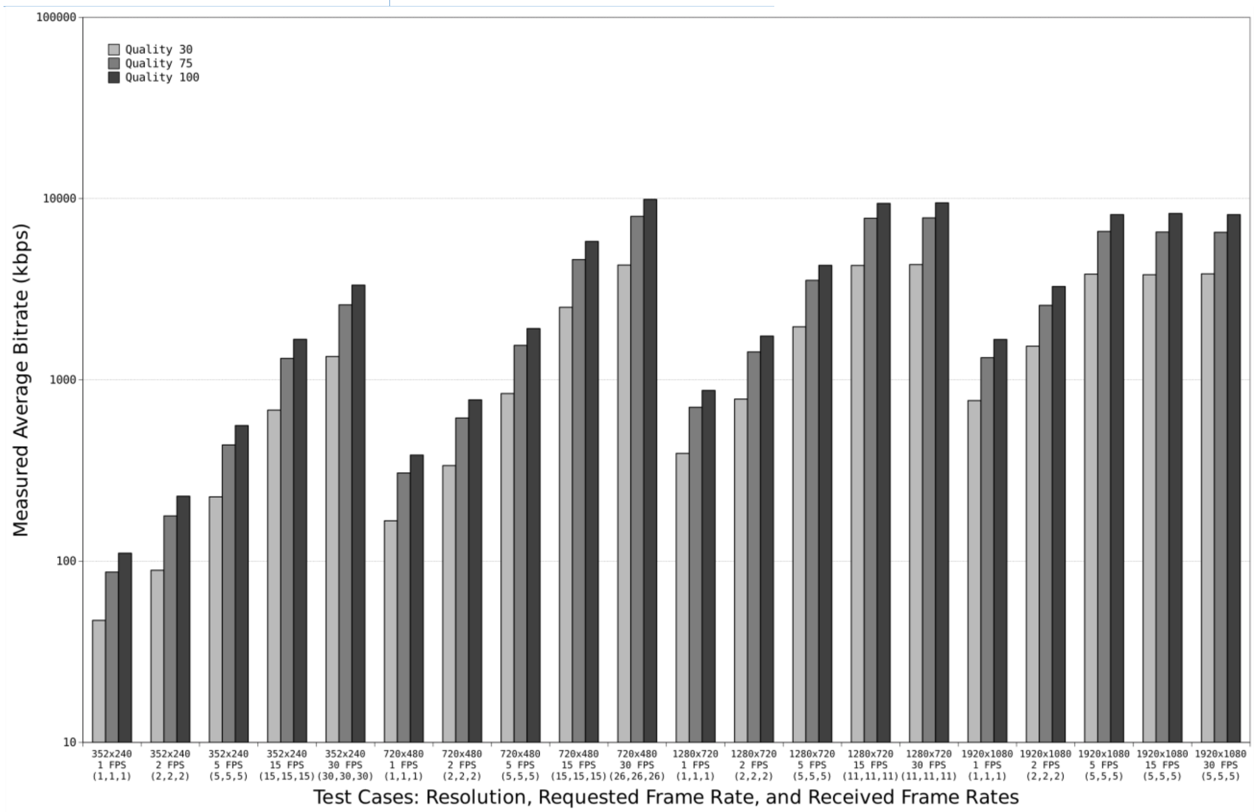

Figure 4.6: Average bitrates for CostarHD RISE 4260HD M-JPEG test

TCP Streaming

This test group consists of 480 tests and employed the streaming configuration of Table 4.31.

Table 4.31: CostarHD RISE 4260HD TCP test streaming configuration

Item	Config
Stream Transport:	***RTP (TCP)***
Encoding:	H.264 (Main)
Bitrate Control Mode:	CBR
Target Bitrate:	80% of maximum rate
GOP Interval:	fixed, 30 frames
Constrained Mode:	off

Our results for this test group were erratic and had low repeatability, especially for low values of R_{targ} and R_{max}. Some tests had very low frame delivery rates, causing poor estimations of frame ratios. The reasons for these sporadic drops in frame delivery are not currently known and merit further investigation.

WTI Viper/Sidewinder HD

Baseline Test

The streaming configuration provided in Table 4.32 was selected for the WTI Viper/Sidewinder HD baseline test group.

Table 4.32: WTI Viper/Sidewinder HD Baseline test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	CBR
Target Bitrate:	80% × 80% of nominal rate
GOP Interval:	fixed, 30 frames

Since this device (with the firmware version we tested) does not support ABR, we selected CBR for its baseline configuration.

Figure 4.7 summarizes the results of the 1,300 tests conducted on the WTI Viper/Sidewinder HD with this (baseline) streaming configuration.

	R_{nom}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x240 @ 1 FPS	7 •	8 •	18 •••	22 •••	35 •••	77 •••	163 •••	334 •••	464 •	537 ••••	540 ••••	560 ••••	560 ••••
320x240 @ 2 FPS	15 •	16 •	19 ••	23 •••	37 •••	86 •••	168 •••	340 •••	516 •••	670 •••	1030 ••••	1007 ••••	1018 ••••
320x240 @ 5 FPS	27 •	29 •	28 •	27 •	37 •••	84 •••	171 •••	341 •••	511 •••	665 •••	1329 •••	2484 •••	2425 ••••
320x240 @ 15 FPS	62 •	60 •	58 •	56 •	51 •	87 •••	168 •••	338 •••	510 •••	662 •••	1320 •••	2641 •••	5269 •••
320x240 @ 30 FPS	102 •	103 •	67 •	94 •	84 •	104 •••	176 •••	342 •••	511 •••	667 •••	1324 •••	2642 •••	5269 •••
640x240 @ 1 FPS	19 •	19 •	19 •	19 •	32 •••	88 •••	169 ••	337 •••	485 •••	652 •••	1156 •••	1222 ••••	1201 ••••
640x240 @ 2 FPS	39 •	32 •	34 •	34 •	40 ••	85 •••	167 •••	335 •••	509 ••	651 •••	1314 •••	2407 •••	2314 ••••
640x240 @ 5 FPS	76 •	64 •	63 •	66 •	62 •	89 •••	168 •••	339 •••	512 •••	661 •••	1324 •••	2639 •••	5171 •••
640x240 @ 15 FPS	184 •	146 •	145 •	140 •	138 •	136 •	178 •••	338 •••	508 •••	661 •••	1318 •••	2636 •••	5288 •••
640x240 @ 30 FPS	267 •	264 •	246 •	31 •	249 •	219 •	330 •	353 •••	511 •••	666 •••	1323 •••	2641 •••	5267 •••
704x480 @ 1 FPS	29 •	31 •	31 •	29 •	33 ••	86 •••	169 ••	320 •••	454 •••	631 •••	1278 •••	2262 •••	2387 ••••
704x480 @ 2 FPS	56 •	53 •	56 •	55 •	56 •	84 •••	173 •••	340 •••	506 •••	683 •••	1327 •••	2703 •••	4647 •••
704x480 @ 5 FPS	105 •	97 •	105 •	105 •	103 •	107 ••	165 •••	337 •••	505 •••	661 •••	1335 •••	2638 •••	5256 •••
704x480 @ 15 FPS	215 •	213 •	199 •	202 •	197 •	212 •	226 ••	337 •••	506 •••	658 •••	1318 •••	2638 •••	5267 •••
704x480 @ 30 FPS	326 •	350 •	351 •	322 •	372 •	346 •	322 •	374 •••	513 •••	665 •••	1322 •••	2640 •••	5283 •••
1280x720 @ 1 FPS	77 •	78 •	68 •	73 •	77 •	77 •	150 •••	340 •••	512 •••	642 •••	1151 •••	2422 •••	4947 •••
1280x720 @ 2 FPS	136 •	137 •	142 •	138 •	141 •	144 •	168 •••	338 •••	496 •••	656 •••	1313 •••	2615 •••	5294 •••
1280x720 @ 5 FPS	262 •	267 •	264 •	262 •	260 •	268 •	257 •	346 •••	505 •••	657 •••	1320 •••	2633 •••	5263 •••
1280x720 @ 15 FPS	524 •	569 •	579 •	566 •	543 •	499 •	501 •	496 •	549 •••	670 •••	1317 •••	2638 •••	5285 •••
1280x720 @ 30 FPS	657 •	791 •	828 •	775 •	782 •	745 •	642 •	728 •	772 ••	780 ••	1333 •••	2643 •••	5280 •••
1920x1080 @ 1 FPS	147 •	128 •	133 •	131 •	123 •	123 •	123 ••	330 •••	474 •••	614 •••	1183 •••	2316 •••	4700 •••
1920x1080 @ 2 FPS	254 •	254 •	260 •	252 •	268 •	245 •	245 •	328 •••	510 •••	657 •••	1309 •••	2599 •••	5270 •••
1920x1080 @ 5 FPS	515 •	515 •	531 •	488 •	504 •	475 •	490 •	485 •	573 •••	669 •••	1319 •••	2640 •••	5286 •••
1920x1080 @ 15 FPS	989 •	917 •	945 •	971 •	985 •	923 •	902 •	920 •	941 •	963 •	1343 •••	2635 •••	5277 •••
1920x1080 @ 30 FPS	1880 •	1909 •	1902 •	1809 •	1797 ••	1729 •	1858 •	1753 •	1895 •	1740 •	2058 ••	2737 •••	5280 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0,\ R_{targ}]$
R : $R \in (t,\ 1.25t]$
R : $R \in (1.25t,\ \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: WTI SW720P
Scene: scene1
Encoding: h264main constant
GOP Mode: 30 f
Quality: 30

Figure 4.7: Stream quality analysis for WTI Viper/Sidewinder HD Baseline test

H.264 High Profile

The purpose of this test group is to compare the performance of a stream using the H.264 "High" profile to the performance of the baseline stream (which uses the H.264 "Main" profile) for the WTI Viper/Sidewinder HD.

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.33.

Table 4.33: WTI Viper/Sidewinder HD H.264 High test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**H.264 (High)**
Bitrate Control Mode:	CBR
Target Bitrate:	80% × 80% of nominal rate
GOP Interval:	fixed, 30 frames

Compared to the baseline (H.264 Main) test group, the following differences can be noted:

- Bitrates were significantly lower for all resolution and frame rate groupings, averaging 8.91% lower.
- Frame ratio results were modestly improved, averaging +3.23% for the 50% nominal rate tests, +3.42% for the 80% nominal rate tests, and +3.37% for the 100% nominal rate tests.

H.264 Baseline Profile

The purpose of this test group is to compare the performance of a stream using the H.264 "Baseline" profile[6] to the performance of the baseline stream (which uses the H.264 "Main" profile) for the WTI Viper/Sidewinder HD.

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.34.

Compared to the baseline (H.264 Main) test group:

- Bitrates were higher for all resolution and frame rate groupings, averaging 13.11% higher. Bitrates were especially higher for higher frame rates (30 FPS averaged 33.38% higher).
- Frame ratio results were modestly worsened, averaging −1.49% for the 50% nominal rate tests, −1.70% for the 80% nominal rate tests, and −2.29% for the 100% nominal rate tests

[6] The H.264 "Baseline" profile is not related in any way to the nomenclature for our "Baseline" test groups (none of which use the H.264 Baseline profile).

Table 4.34: WTI Viper/Sidewinder HD H.264 Baseline test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**H.264 (Baseline)**
Bitrate Control Mode:	CBR
Target Bitrate:	80% × 80% of nominal rate
GOP Interval:	fixed, 30 frames

M-JPEG

This test group consists of 75 tests and employed the streaming configuration of Table 4.35.

Table 4.35: WTI Viper/Sidewinder HD M-JPEG test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	**M-JPEG**
Bitrate Control Mode:	**N/A**
Target Bitrate:	**N/A**
GOP Interval:	**N/A**

Three M-JPEG quality levels were chosen for testing: 30, 75, and 100. The test results are summarized in Figure 4.8. Relative to the baseline test group, the following differences can be noted:

- The average bitrates for non-network-limited tests were significantly higher when resolution or frame rate is high.
- Frame delivery suffered at higher frame rates for some high-resolution and high-quality scenarios.

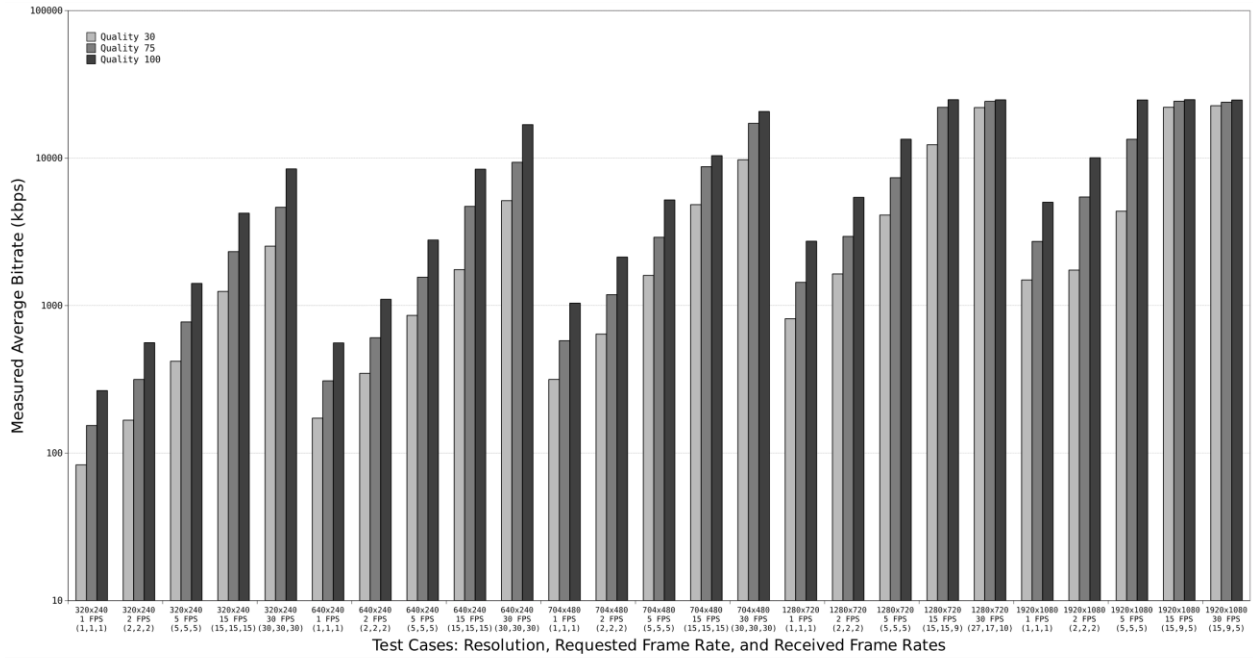

Figure 4.8: Average bitrates for WTI Viper/Sidewinder HD M-JPEG test

Varying GOP Interval with Frame Rate

To explore the effects of choosing a GOP interval based on a fixed duration rather than a fixed number of frames, for each test in this test group, we dynamically selected a GOP interval such that the GOP would have a duration of 5 seconds:

Table 4.36: Correlation between frame rate and GOP interval for a GOP duration of 5 seconds

Frame Rate (kbps)	GOP Interval
1	5
2	10
5	25
15	75
30	150

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.37.

Table 4.37: WTI Viper/Sidewinder HD Varying GOP Interval test streaming configuration

Item	Config
Stream Transport:	**RTP (UDP)**
Encoding:	H.264 (Main)
Bitrate Control Mode:	CBR
Target Bitrate:	80% × 80% of nominal rate
GOP Interval:	**fixed, *5r* frames**

As expected, the performance of this test group (relative to the baseline test group which uses a GOP interval of 30 for all tests), depends on frame rate. The key findings are as follows:

- For the 1, 2, and 5 FPS tests, for which the GOP interval values were lower than the baseline group's value of 30, I-frames comprised a larger portion of the stream and higher average bitrates were observed (+19.48%, +7.91%, and +0.56% respectively).
- For the 15 FPS tests, for which the GOP interval values were higher than the baseline group's value of 30, I-frames comprised a smaller portion of the stream and lower average bitrates were observed (−5.78%).
- For the 30 FPS tests, although the GOP interval values were higher than the baseline group's value of 30, average bitrates were nearly unchanged (+0.15). At this time it is not known why an improvement in bitrate was not seen in these cases.

TCP Streaming

This test group consists of 1,300 tests and employed the streaming configuration of Table 4.38.

Our results for this test group were erratic and had low repeatability. Some tests had very low frame delivery rates, causing poor estimations of frame ratios. The reasons for these sporadic drops in frame delivery are not known at this time and merit further investigation.

Table 4.38: WTI Viper/Sidewinder HD TCP test streaming configuration

Item	Config
Stream Transport:	***RTP (TCP)***
Encoding:	H.264 (Main)
Bitrate Control Mode:	CBR
Target Bitrate:	80% × 80% of nominal rate
GOP Interval:	fixed, 30 frames

Static Image Testing

To gain insight into the general range of frame sizes (i.e., in bytes) that can be expected when fetching static images from our selected devices, and how frame size correlates with image quality settings, we performed a series of static image tests.

The results of these tests may be of use in the selection and configuration of CCTV devices for rural sites with network links of insufficient capacity for video streaming.

Scene Selection

To cover a reasonable range of levels of scene brightness and detail, we selected thirteen scenes for these tests, as illustrated in Figure 4.9.

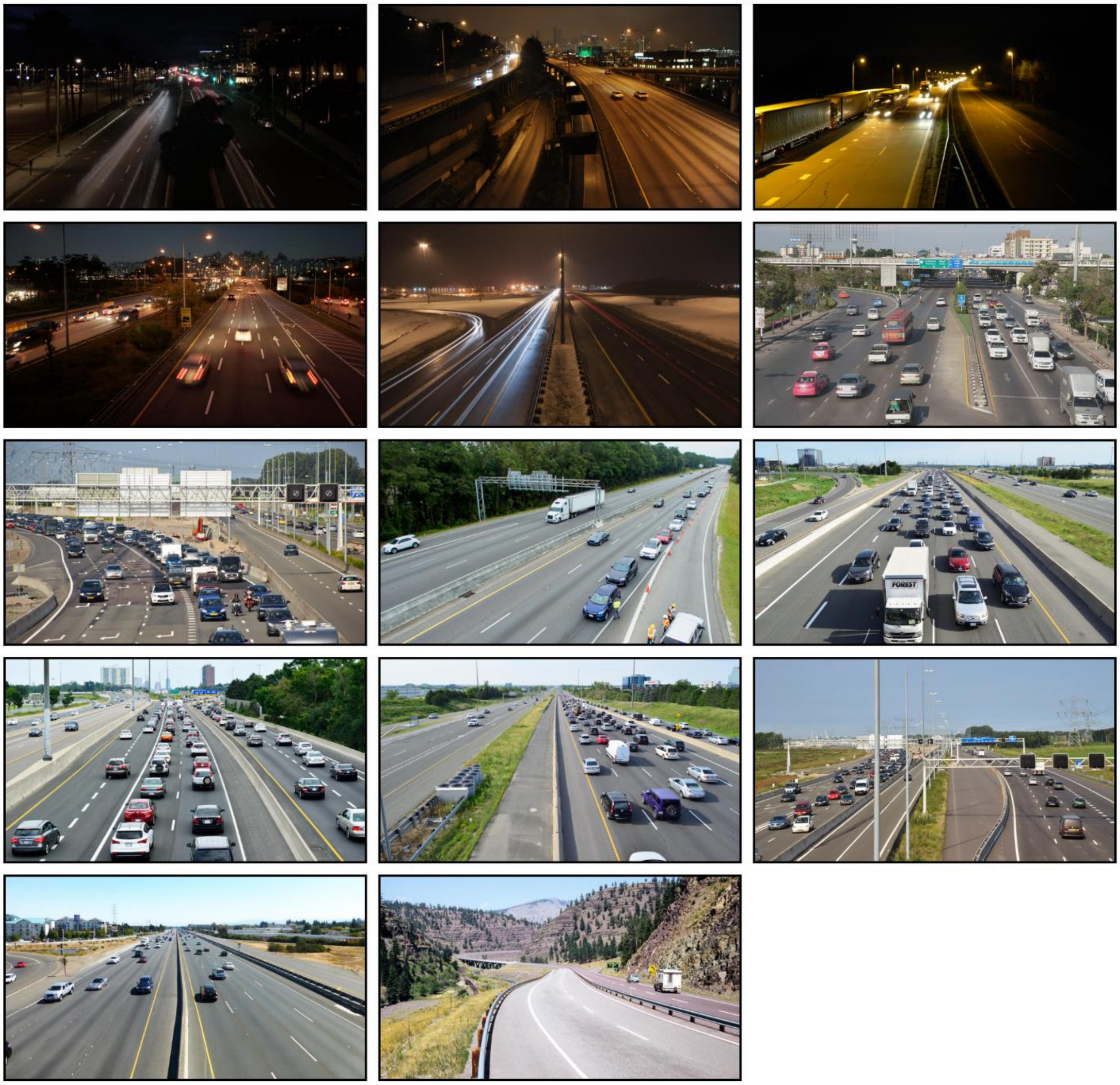

Figure 4.9: Scenes for static image tests[7]

[7] Attribution for static images in Fig. 4.9, proceeding left to right and top to bottom, are as follows: 1) Panasonic Connect Europe, 5.5 4K Camera Road in Thailand No 2 (https://www.youtube.com/watch?v=F4bICvLY024); 2) Raban Haaijk, Seoul Highway at Night (https://flickr.com/photos/haaijk/22776105458/); 2) Raban Haaijk, Seoul Highway at Night (https://flickr.com/photos/haaijk/22776105458/); 3) Sergei Gussev, Huntington Beach (https://flickr.com/photos/sergeigussev/46708670631/); 4) Timon91, Truck chaos near De Lutte (https://flickr.com/photos/timon91/5054604689/); 5) Wonderlane, Highway 5 from the north of Seattle, wet night, raining, overpasses, a few cars, mist, winter. Near Lake Union, Seattle, Washington, USA (https://flickr.com/photos/wonderlane/5377520184/); 6) Olivier Taillon, Highway (https://flickr.com/photos/olitaillon/8378077545/); 7) Josbert Lonnee, Oude en

Data Collection

All the devices tested encode static images as JPEG and allow the specification of either a "compression" or a "quality" parameter to configure the encoding.

Table 4.39: Compression/quality parameters for static image acquisition

Device	Parameter	Range	Image Quality Scale
Axis Q8752-E	Compression	[0, 100]	high → low
Bosch MIC inteox 7100i	JpegQuality	[1, 100]	high → low
CostarHD RISE 4260HD	Quality	[1, 99]	low → high
WTI Viper/Sidewinder HD	Quality	[0, 100]	low → high

We chose eleven compression/quality levels for testing, ranging from 0 to 100, incrementing by 10. If levels 0 or 100 were not supported by a device, its value was substituted with 1 or 99, respectively.

For each scene, and for each resolution class,[8] a single image was acquired from each device, for each of the compression/quality levels.

nieuwe rijbanen A1 naast elkaar (https://flickr.com/photos/98552965@N05/29313083556/); 8) South Carolina National Guard, S.C. Guard Assist With Hurricane Matthew Preparations (https://flickr.com/photos/scguard/29542713304/); 9) Josbert Lonnee, Oude en nieuwe rijbanen A1 naast elkaar (https://flickr.com/photos/98552965@N05/29059313760/); 10) United States Department of Agriculture, Natural Resources Conservation Service, Montana, Photo courtesy of USDA Natural Resources Conservation Service (https://flickr.com/photos/160831427@N06/25190489478/); 11) Open Grid Scheduler / Grid Engine, Highway (https://flickr.com/photos/opengridscheduler/43796685961/); 12) Open Grid Scheduler / Grid Engine, Highway (https://flickr.com/photos/opengridscheduler/42893196575/); 13) Open Grid Scheduler / Grid Engine, Highway 404 & Highway 401 (https://flickr.com/photos/opengridscheduler/20102270135/); 14) Mike Linksvayer, P1020940 (https://flickr.com/photos/mlinksva/8018436373/). **Licensing is as follows: Image 1 "fair use"; images 2-6 "CC BY 2.0 DEED" https://creativecommons.org/licenses/by/2.0/; images 7-14 public domain.**

[8] The Bosch MIC inteox 7100i did not support the same set of resolutions for static images as it did for streaming. Hence, the following resolutions were used for static image testing on this device: 256x144, 352x198, 512x288, 1280x720, and 1920x1080.

Static Image Results

Frame size averages and range (error bars) in KiB were as shown in Figures 4.10-4.12.

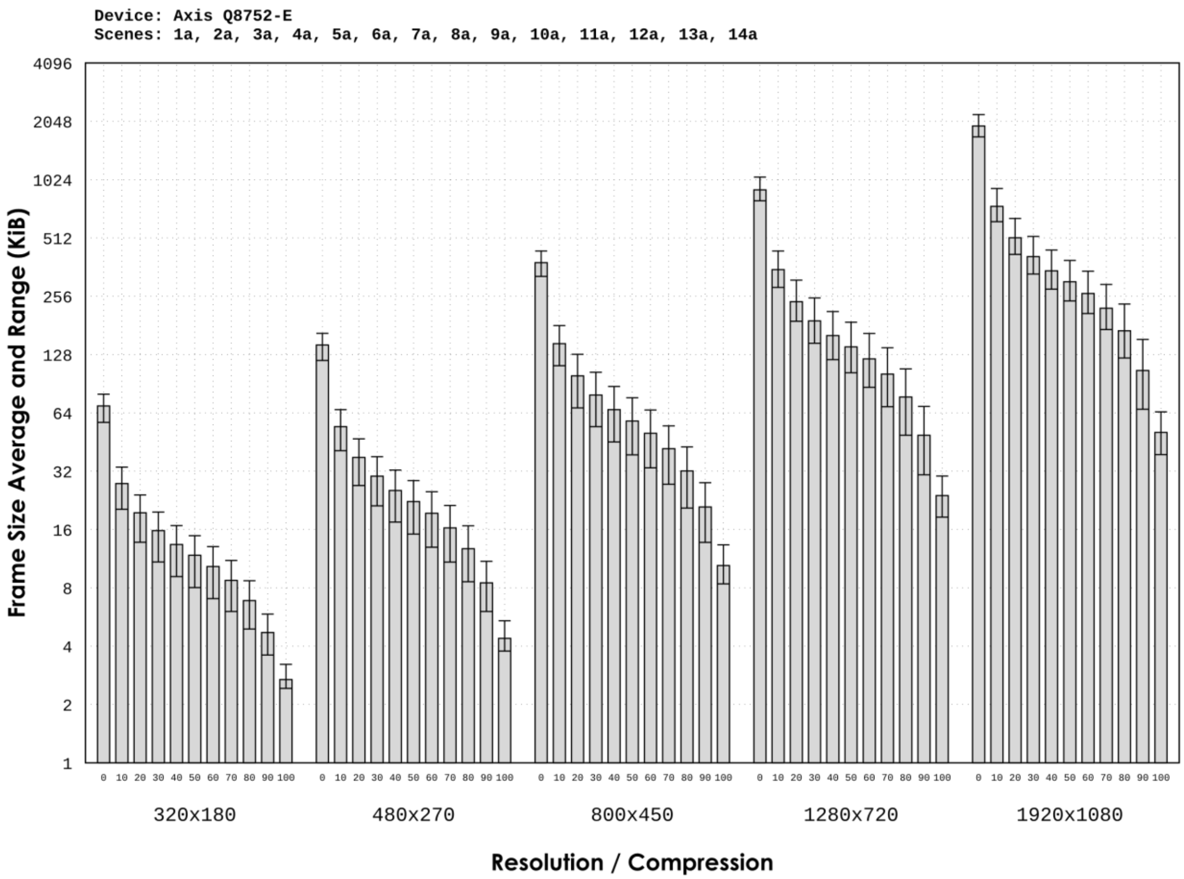

Figure 4.10: Image sizes for Axis Q8752-E JPEG test

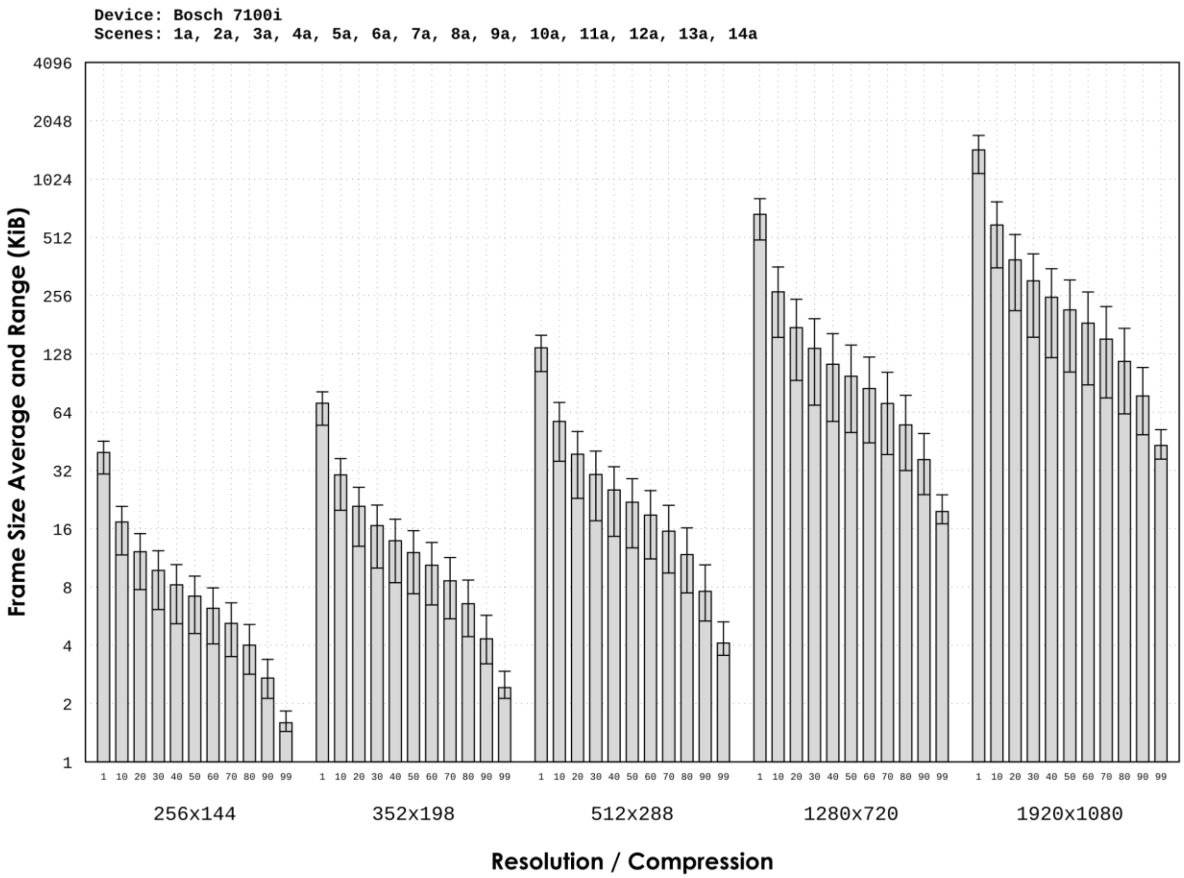

Figure 4.11: Image sizes for Bosch MIC inteox 7100i JPEG test

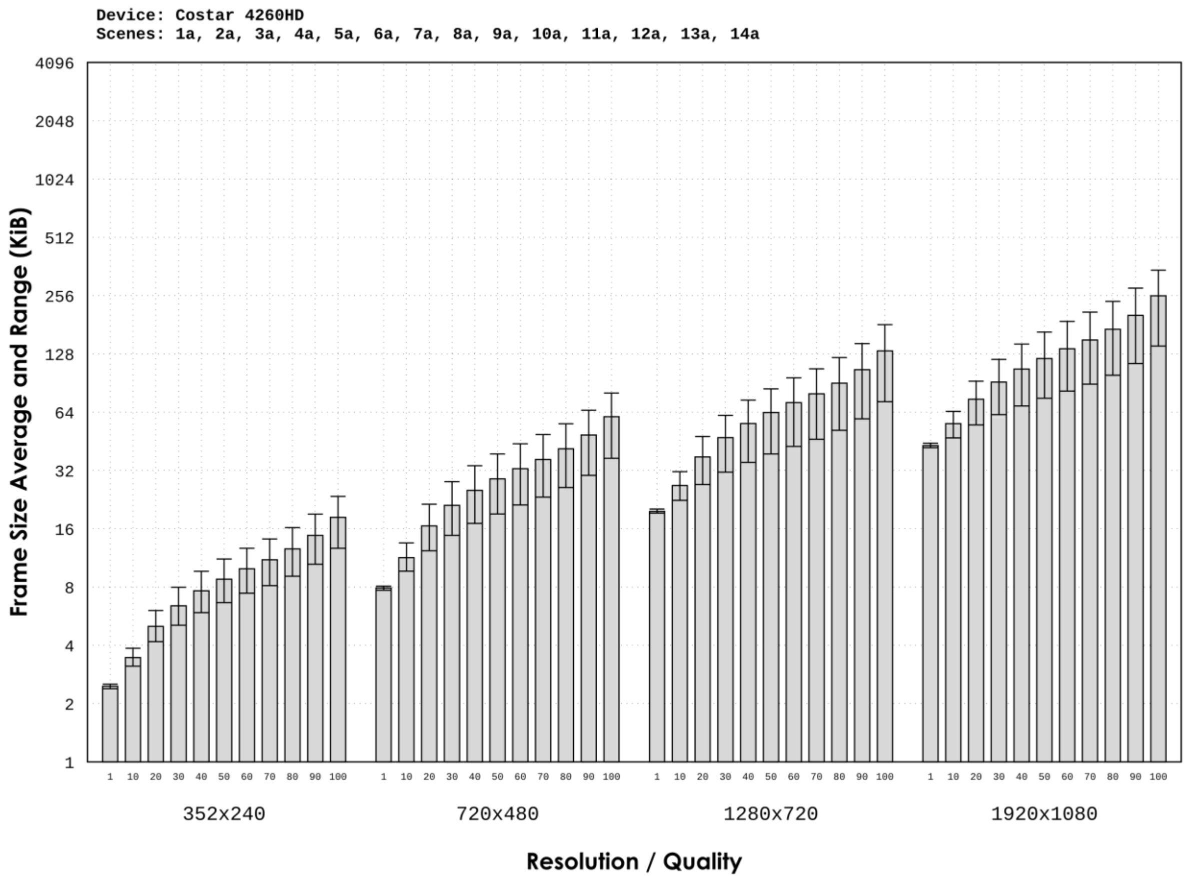

Figure 4.12: Image sizes for CostarHD RISE 4260HD JPEG test

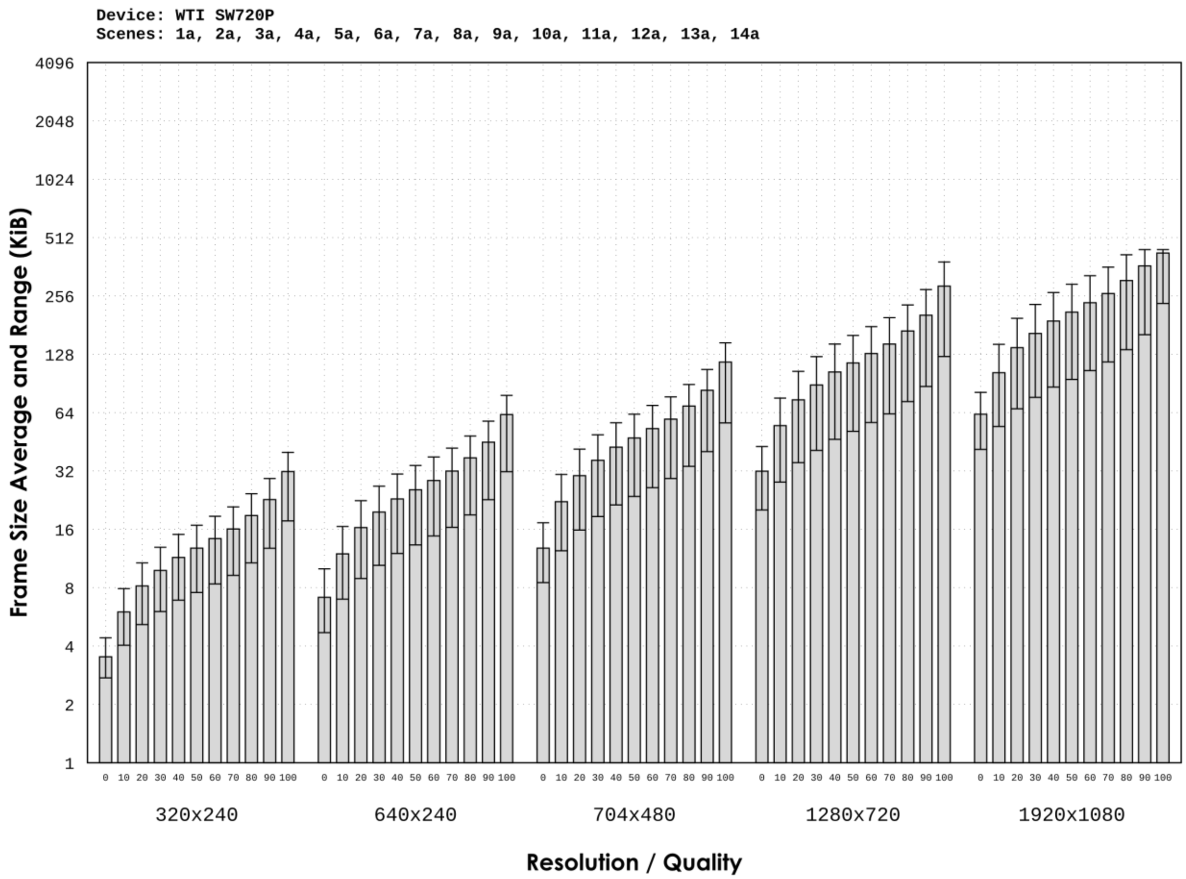

Figure 4.13: Image sizes for WTI Viper/Sidewinder HD JPEG test

While frame sizes varied as expected per device, appreciable differences in frame size were observed between the devices, even for similar resolution and compression/quality parameters. This is likely due, at least in part, to differences in JPEG implementations. Other contributing factors may be differences in the CCTV itself (e.g., exposure, iris, color, gain, analog-to-digital conversion, optical differences) as well as internal image processing algorithms.

Subjective examination of the resulting images reveals that, at least for our test scenes, reasonable images can be acquired from the Axis Q8752-E at compression levels up through 70 or 80, from the Bosch MIC inteox 7100i at JpegQuality[9] levels up through 70 or 80, from the CostarHD RISE 4260HD at Quality levels down to 40 or 30, and from the WTI Viper/Sidewinder HD at Quality levels down to 30 or 20. Artifacts are technically always present with any destructive image compression scheme, and they generally increase in proportion to the degree of compression. However, these values are the thresholds beyond which substantial artifacts were observed for our scenes.

[9] Somewhat of a misnomer in this case, as higher values produce lower quality images.

Chapter 5:
Summary Discussion and Conclusions

Axis Q8752-E

H.264 Main vs. H.264 High vs. H.265 Main

In our testing on this device, H.264 High slightly outperformed H.264 Main for lower resolutions and frame rates but underperformed for higher resolutions and frame rates.

Compared to both H.264 Main and H.264 High, bitrates for H.265 Main averaged lower across all resolutions and frame rates and were substantially lower overall (−9.88% compared to H.264 Main, and −10.48% compared to H.264 High).

If H.265 is supported by the decoder(s), H.265 is likely to be the best choice. If not, we suggest H.264 High for lower resolutions and frame rate, and H.264 Main for higher resolutions and frame rates. However, the differences between the two were relatively modest, so other factors such as decoder compatibility or scene type may factor into this choice.

M-JPEG

Bitrates of M-JPEG streams are typically much higher than those of H.264 or H.265 streams. For this device, bitrates for the M-JPEG test group averaged over an order of magnitude higher than the baseline test group (See Figure 4.2). Unless required for compatibility reasons, or when difficulties are encountered configuring H.264 or H.265 streams for low-bandwidth links (e.g., ISDN/POTS), we recommend against choosing M-JPEG for most highway CCTV applications.

ABR vs. MBR vs. VBR

For MBR, our non-network-limited tests indicated higher bitrates than ABR, and our network-limited tests indicated higher frame loss. Since ABR is a more advanced bitrate control scheme, this is not particularly surprising.

VBR is a bitrate control scheme that prioritizes visual quality, can result in unpredictable bitrates, and is generally not a good fit for highway surveillance CCTVs, especially in rural areas.

For the Axis Q8752-E, we suggest ABR as a good starting point for most highway CCTV applications.

GOP Interval

The GOP interval is an important component of an H.264 or H.265 stream configuration, especially when targeting low-bitrate communications links. Selecting an appropriate GOP interval is fundamentally a trade-off between bitrate and how long it takes for a stream to recover from data loss. With the Axis Q8752-E, GOP intervals can be controlled in two ways:

- using the fixed GOP mode and configuring a single GOP interval value
- using the Zipstream dynamic GOP mode and configuring a range of values to which to confine the GOP interval

Our test results demonstrate that stream bitrates can be appreciably lowered by using these methods in conjunction with appropriately chosen parameter values.

While other factors (e.g., playback seeking granularity for recorded streams) can play a role in GOP interval selection, for simple live-streaming applications such as field-to-TMC transport, the main factors involved are bitrate, recovery time, and likelihood of stream corruption (network quality). As seen in our test results, the choice of longer GOP intervals can result in bitrate reduction. For very reliable network connections which are unlikely to result in significant frame loss or corruption, such a choice can be beneficial. However, for lower-quality network connections in which stream corruption is more likely, lower GOP intervals may be preferable (even at the cost of higher bitrates) since they generally allow for quicker stream recovery after corruption.

As a starting point in the selection process, we recommend deciding a maximum acceptable value d (in seconds) for stream recovery time from a single data loss incident. An appropriate maximum GOP interval n can then be calculated by multiplying d by the desired frame rate (per second) r:

$$n = dr$$

GOP intervals longer than n frames may result in stream recovery (i.e., from data loss incidents) periods longer than d seconds. This n value can then be used as a reasonable initial value for testing, either as the GOP interval value for the fixed GOP mode, or as the upper bound of the range for the Zipstream dynamic GOP mode. If the bitrate remains higher than desired, n can be increased, but only at the cost of increasing d or reducing r.

With the Zipstream dynamic GOP mode, it’s also important to select an appropriate value for the lower bound of the GOP interval range, especially at lower frame rates, as the algorithm may select values that are too low for some streaming scenarios over low-bitrate network connections.

Compression

Our test results demonstrate that bitrates can be decreased dramatically on the Axis Q8752-E by increasing its "compression" parameter beyond the default value of 30. Although compression reduces visual quality, we found that it can be increased substantially without making the stream unusable. Compared to the default level of 30, we found that, for our test scene, a compression level of 100 resulted in an average bitrate reduction of 57.77% as well as a significant reduction in dropped frames.

For sites with limited network capacity, especially in cases where perfect visual quality is unnecessary, we recommend experimenting with higher compression levels.

Zipstream

Zipstream is a set of proprietary encoder enhancements that Axis recommends enabling for most streams [4].

Zipstream is primarily configured using the Zipstream Strength parameter which can be either off, 10, 20, 30, 40, or 50. It also supports other features such as dynamic GOP intervals and dynamic frame rate.

The Zipstream Strength parameter defaults to 10, likely because Axis claims that this value results in "no visible effect in most scenes" [5], and because values other than 10 or off may not be compatible with all clients/decoders [4].

We tested Zipstream with Strength parameters of 10, 30, and 50, yielding the following notable results:

- Strength 10: Bitrates reduced an average of 11.12%.
- Strength 30: Bitrates reduced an average of 15.61%.
- Strength 50: Bitrates reduced when ABR target/max values are realistic, otherwise bitrates increased substantially. The reasons for this are unclear.

These observations support the use of Zipstream, especially at lower strength levels.

TCP vs. UDP

While there are situations where, with certain network conditions and streaming configurations, switching from UDP to TCP may appear to provide superior results, we believe that this often means that the streaming configuration used was not a good match for the network conditions in the first place. In these cases, switching to TCP may seem to improve the stream, but often comes with other side effects such as progressive degradation or periodic skips.

We recommend using UDP for all real-time field-to-TMC streams unless TCP is required for network policy reasons (e.g., firewall configurations that will not allow UDP streaming).

In our testing on this device, using TCP resulted in bitrates that averaged 5.60% higher than in comparable tests with UDP. Frame loss was also slightly higher for TCP in constrained network conditions.

JPEG

JPEG image size statistics from our test results can be found in Figure 4.10. Subjective examination of the resulting images reveals that, at least for our test scenes, reasonable images can be acquired from this device at compression levels up through 70 or 80. For images on the lower end of the resolution range, using compression levels 50 or lower may be best.

Bosch MIC inteox 7100i

A Note on Bitrates

For many encoding modes, this device (at least with firmware 8.46.0030) appears to consistently produce bitrates higher than requested, even though a reasonable stream can be created within the specified target and maximum bitrates. As one example, our ungoverned 768x432 @ 5 FPS test for link class 13 (nominal rate 8000 kbps) specified a target rate of 5120 kbps and a maximum rate of 6400. The encoder responded with a stream averaging 6588 kbps, a rate that is above both the target and maximum rates. However, it's clear that the encoder is able to produce a stream within the bounds requested because, during the corresponding test for link class 6 (nominal rate 128 kbps, target rate 81 kbps, maximum rate 102 kbps), the encoder produced a stream averaging 108 kbps, a rate well within the target range of the test for link class 13.

Until more is understood about the reason for this behavior, or until it changes, it is recommended to use extremely conservative values for the maximum and target bitrates (e.g., a maximum bitrate that is 30% of the nominal network bitrate, and a target bitrate that is 80% of the maximum bitrate) on this device.

H.264 High vs. H.265 Main

In our testing on this device, H.265 Main significantly outperformed H.264 High across all resolution and frame rate categories, with bitrates averaging 14.44% lower overall.

If H.265 is supported by the decoder(s), H.265 is likely to be the best choice for this device.

M-JPEG

Bitrates of M-JPEG streams are typically much higher than those of H.264 or H.265 streams. For this device, bitrates for the M-JPEG test group averaged significantly higher than the baseline test group, especially for higher resolutions and frame rates. Unless required for compatibility reasons, or when difficulties are encountered configuring H.264 or H.265 streams for low-bandwidth links (e.g., ISDN/POTS), we recommend against choosing M-JPEG for most highway CCTV applications.

GOP Interval

The GOP interval is an important component of an H.264 or H.265 stream configuration, especially when targeting low-bitrate communications links. Selecting an appropriate GOP interval is fundamentally a trade-off between bitrate and how long it takes for a stream to recover from data loss. With the Bosch MIC inteox 7100i, GOP intervals can be specified as a constant value or the dynamic ("auto I-frame distance") GOP mode can be used.

Our test results demonstrate that stream bitrates can be appreciably lowered by using these methods in conjunction with appropriately chosen parameter values.

While other factors (e.g., playback seeking granularity for recorded streams) can play a role in GOP interval selection, for simple live-streaming applications such as field-to-TMC transport, the main factors involved are bitrate, recovery time, and likelihood of stream corruption (network quality). As seen in our test results, the choice of longer GOP intervals can result in bitrate reduction. For very reliable network connections which are unlikely to result in significant frame loss or corruption, such a choice can be beneficial. However, for lower-quality network connections in which stream corruption is more likely, lower GOP intervals may be preferable (even at the cost of higher bitrates) since they generally allow for quicker stream recovery after corruption.

As a starting point in the selection process, we recommend deciding a maximum acceptable value d (in seconds) for stream recovery time from a single data loss incident. An appropriate maximum GOP interval n can then be calculated by multiplying d by the desired frame rate (per second) r:

$n = dr$

GOP intervals longer than n frames may result in stream recovery (i.e., from data loss incidents) periods longer than d seconds. This n value can then be used as a reasonable initial value for testing. If the bitrate remains higher than desired, n can be increased, but only at the cost of increasing d or reducing r.

Using this device's dynamic ("auto I-frame distance") GOP mode did improve bitrates by a few percent (2.44% lower overall), resulting in the average GOP intervals per frame-rate category listed in Table 5.1.

Table 5.1: Compression/quality parameters for static image acquisition

Frame Rate Category	Average GOP Interval	*gop ÷ framerate*
1 FPS	13.4	13.4
2 FPS	28.0	14.0
5 FPS	68.7	13.7
15 FPS	110.8	7.4
30 FPS	138.8	4.6

TCP vs. UDP

While there are situations where, with certain network conditions and streaming configurations, switching from UDP to TCP may appear to provide superior results, we believe that this often means that the streaming configuration used was not a good match for the network conditions in the first place. In these cases, switching to TCP may seem to improve the stream, but often comes with other side effects such as progressive degradation or periodic skips.

We recommend using UDP for all real-time field-to-TMC streams unless TCP is required for network policy reasons (e.g., firewall configurations that will not allow UDP streaming).

In our testing on this device, using TCP resulted in bitrates that averaged 4.53% higher than in comparable tests with UDP. Frame loss results were mixed.

JPEG

JPEG image size statistics from our test results can be found in Figure 4.11. Subjective examination of the resulting images reveals that, at least for our test scenes, reasonable images can be acquired from this device at JpegQuality (compression) levels up through 70 or 80. For images on the lower end of the resolution range, using JpegQuality (compression) levels 50 or lower may be best.

CostarHD RISE 4260HD

H.264 High vs. H.264 Main

In our testing on this device, H.264 High delivered results nearly indistinguishable from H.264 Main. Decoder compatibility is likely to be the dominant factor in making this choice.

Constrained Mode

This device has a featured called "Video Constrained Mode". We were unable to find much documentation about this function other than a brief mention that its purpose may have something to do with adherence to the specified maximum bitrate (R_{max}).

Our test results with this mode enabled were nearly indistinguishable from the baseline test group (for which it was disabled). Future investigation is merited.

M-JPEG

Bitrates of M-JPEG streams are typically much higher than those of H.264 streams. However, it's important to note that this device does not allow the specification of H.264 target bitrates (Rtarg) less than 256 kbps, so M-JPEG may be a better choice than H.264 for some streams with lower resolutions or frame rates. See Figure 4.5 and Figure 4.6 as a starting point for making this decision.

GOP Interval

The GOP interval is an important component of an H.264 or H.265 stream configuration, especially when targeting low-bitrate communications links. Selecting an appropriate GOP interval is fundamentally a trade-off between bitrate and how long it takes for a stream to recover from data loss. With the CostarHD RISE 4260HD, GOP intervals can be specified only as a constant value in the range [1, 600].

Our test results demonstrate that stream bitrates can be appreciably lowered by using these methods in conjunction with appropriately chosen parameter values.

While other factors (e.g., playback seeking granularity for recorded streams) can play a role in GOP interval selection, for simple live-streaming applications such as field-to-TMC transport, the main factors involved are bitrate, recovery time, and likelihood of stream corruption (network quality). As seen in our test results, the choice of longer GOP intervals can result in bitrate reduction. For very reliable network connections which are unlikely to result in significant frame loss or corruption, such a choice can be beneficial. However, for lower-quality network connections in which stream corruption is more likely, lower GOP intervals may be preferable (even at the cost of higher bitrates) since they generally allow for quicker stream recovery after corruption.

As a starting point in the selection process, we recommend deciding a maximum acceptable value d (in seconds) for stream recovery time from a single data loss incident. An appropriate maximum GOP interval n can then be calculated by multiplying d by the desired frame rate (per second) r:

$n = dr$

GOP intervals longer than n frames may result in stream recovery (i.e., from data loss incidents) periods longer than d seconds. This n value can then be used as a reasonable initial value for testing. If the bitrate remains higher than desired, n can be increased, but only at the cost of increasing d or reducing r.

TCP vs. UDP

While there are situations where, with certain network conditions and streaming configurations, switching from UDP to TCP may appear to provide superior results, we believe that this often means that the streaming configuration used was not a good match for the network conditions in the first place. In these cases, switching to TCP may seem to improve the stream, but often comes with other side effects such as progressive degradation or periodic skips.

We recommend using UDP for all real-time field-to-TMC streams unless TCP is required for network policy reasons (e.g., firewall configurations that will not allow UDP streaming).

In our testing on this device, using TCP resulted in mixed results that are difficult to interpret. Future investigation is merited.

JPEG

JPEG image size statistics from our test results can be found in Figure 4.12. Subjective examination of the resulting images reveals that, at least for our test scenes, reasonable images can be acquired from this device at Quality levels down to 40 or 30. For images on the lower end of the resolution range, using Quality levels 60 or higher may be best.

WTI Viper/Sidewinder HD

H.264 High vs. H.264 Baseline vs. H.264 Main

In our testing on this device, H.264 High delivered better results than H.264 Main. Bitrates were significantly lower for all resolution and frame rate groupings, averaging 8.91% lower. Frame ratio results were modestly improved, averaging 3.23% higher for the 50% nominal rate tests, 3.42% higher for the 80% nominal rate tests, and 3.37% higher for the 100% nominal rate tests.

H.264 Baseline, however, delivered inferior results compared to H.264 Main. Bitrates were significantly higher for all resolution and frame rate groupings, averaging 13.11% higher. Frame delivery was modestly lower, averaging 1.49% lower for the 50% nominal rate tests, 1.70% lower for the 80% nominal rate tests, and 2.29% lower for the 100% nominal rate tests.

Excluding other factors (e.g., decoder compatibility, scene type), H.264 High may be the best choice on this device.

M-JPEG

Bitrates of M-JPEG streams are typically much higher than those of H.264 streams. For this device, bitrates for the M-JPEG test group were much higher for many streams, particularly those with higher resolutions or frame rates (see Figure 4.8. Unless required for compatibility reasons, or when difficulties are encountered configuring H.264 or H.265 streams for low-bandwidth links (e.g., ISDN/POTS), we recommend against choosing M-JPEG for most highway CCTV applications.

GOP Interval

The GOP interval is an important component of an H.264 or H.265 stream configuration, especially when targeting low-bitrate communications links. Selecting an appropriate GOP interval is fundamentally a trade-off between bitrate and how long it takes for a stream to recover from data loss. With the WTI Viper/Sidewinder HD, GOP intervals can be specified only as a constant value in the range [1, 450].

Our test results demonstrate that stream bitrates can be appreciably lowered by using these methods in conjunction with appropriately chosen parameter values.

While other factors (e.g., playback seeking granularity for recorded streams) can play a role in GOP interval selection, for simple live-streaming applications such as field-to-TMC transport, the main factors involved are bitrate, recovery time, and likelihood of stream corruption (network quality). As seen in our test results, the choice of longer GOP intervals can result in bitrate reduction. For very reliable network connections which are unlikely to result in significant frame loss or corruption, such a choice can be beneficial. However, for lower-quality network connections in which stream corruption is more likely, lower GOP intervals may be preferable (even at the cost of higher bitrates) since they generally allow for quicker stream recovery after corruption.

As a starting point in the selection process, we recommend deciding a maximum acceptable value *d* (in seconds) for stream recovery time from a single data loss incident. An appropriate maximum GOP interval n can then be calculated by multiplying d by the desired frame rate (per second) r:

$n = dr$

GOP intervals longer than n frames may result in stream recovery (i.e., from data loss incidents) periods longer than d seconds. This n value can then be used as a reasonable initial value for testing. If the bitrate remains higher than desired, n can be increased, but only at the cost of increasing d or decreasing r.

TCP vs. UDP

While there are situations where, with certain network conditions and streaming configurations, switching from UDP to TCP may appear to provide superior results, we believe that this often means that the streaming configuration used was not a good match for the network conditions in the first place. In these cases, switching to TCP may seem to improve the stream, but often comes with other side effects such as progressive degradation or periodic skips.

We recommend using UDP for all real-time field-to-TMC streams unless TCP is required for network policy reasons (e.g., firewall configurations that will not allow UDP streaming).

In our testing on this device, using TCP resulted in mixed results that are difficult to interpret. Future investigation is merited.

JPEG

JPEG image size statistics from our test results can be found in Figure 4.13. Subjective examination of the resulting images reveals that, at least for our test scenes, reasonable images can be acquired from this device at Quality levels down to 30 or 20 for medium-large image resolutions. For images on the lower end of the resolution range, using Quality levels 50 or higher may be best.

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Appendix A: CCTV Operating Conditions and Characteristics

Based on initial discussions with the PM and project champion, the following CCTV operating conditions and characteristics have been identified as of interest in this study:

- Testbeds
  - Existing
  - Need to construct
- District type
  - Rural
- Bandwidth
  - Ultra-low (up to 10 kbps)
  - Low (10 kbps – 128 kbps)
  - Medium (128 kbps – 1.5 Mbps) , if available
  - High (greater than 1.5 Mbps), if available
- JPEG needs for CWWP2
- H.264 needs for streaming / Wowza
  - RTMP
  - RTSP
  - HDS
  - MJPEG
- Decoding digital video at the district office
- Environments
  - Coastal
  - Mountain
  - Desert
  - Metropolitan, if available
- Operating temperature range
- Form factor
  - Integrated CCTV
    - Dome
    - Pole-mounted 360 deg PTZ
  - Stand-alone enclosure
    - Rack-mountable
    - Din-rail
- Cabling and physical interface
  - Analog
    - BNC (video)
    - Serial (RS-422)
  - Digital
    - Ethernet
- Interfaces
  - HTTP
  - SSH
  - SFTP
  - Others
- Scene lighting - function of CCTV unit
  - Luminaire
  - Moonlight
  - Headlights
  - Integration

Appendix B: Stream Quality Analysis and Average Bitrate Charts

This appendix contains the Stream Quality Analysis and Average Bitrate charts for the test groups in this study.

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	6 •	9 •	15 •••	17 •••	26 •	47 ••••	52 ••••	53 ••••	50 ••••	50 ••••	50 ••••	52 ••••	51 ••••
320x180 @ 2 FPS	9 •	12 •	18 ••	26 •••	37 •••	85 •••	77 ••••	89 ••••	90 ••••	85 ••••	86 ••••	82 ••••	89 ••••
320x180 @ 5 FPS	11 •	15 •	21 ••	23 •••	40 •••	89 •••	154 •••	164 ••••	160 ••••	153 ••••	133 ••••	165 ••••	149 ••••
320x180 @ 15 FPS	19 •	22 •	35 •	38 •	44 ••	80 •••	169 •••	295 •••	400 •••	422 ••••	373 ••••	424 ••••	407 ••••
320x180 @ 30 FPS	32 •	32 •	43 •	50 •	69 •	83 •••	152 •••	320 •••	409 •••	434 •••	614 ••••	661 ••••	695 ••••
480x270 @ 1 FPS	7 •	10 •	17 ••	20 ••	27 •••	51 ••	90 ••••	86 ••••	89 ••••	92 ••••	89 ••••	92 ••••	89 ••••
480x270 @ 2 FPS	10 •	14 •	24 ••	27 •	34 •••	77 •••	151 •••	159 ••••	156 ••••	147 ••••	138 ••••	150 ••••	155 ••••
480x270 @ 5 FPS	19 •	23 •	27 •	32 •	39 •••	89 •••	149 •••	275 •••	244 ••••	276 ••••	279 ••••	268 ••••	283 ••••
480x270 @ 15 FPS	37 •	37 •	41 •	45 •	64 •	87 •••	157 •••	325 •••	483 •••	531 •••	666 ••••	642 ••••	643 ••••
480x270 @ 30 FPS	58 •	58 •	60 •	63 •	79 •	137 •	151 •••	304 •••	431 •••	592 •••	1013 ••••	1062 ••••	1100 ••••
800x450 @ 1 FPS	20 •	20 •	21 •	25 •	34 ••	70 •••	146 •••	229 •••	264 ••••	274 ••••	259 ••••	260 ••••	244 ••••
800x450 @ 2 FPS	24 •	25 •	28 •	27 •	45 •	89 •••	156 •••	253 ••	331 •••	430 ••••	448 ••••	495 ••••	444 ••••
800x450 @ 5 FPS	56 •	54 •	54 •	63 •	61 •	96 •••	180 •••	369 •••	438 •••	664 •••	876 ••••	823 ••••	819 ••••
800x450 @ 15 FPS	103 •	106 •	102 •	103 •	100 •	124 •	197 •••	304 •••	504 •••	682 •••	1046 •••	2034 ••••	1747 ••••
800x450 @ 30 FPS	157 •	158 •	156 •	155 •	158 •	179 •	304 •	337 •••	449 •••	592 •••	1240 •••	2334 •••	3016 ••••
1280x720 @ 1 FPS	51 •	52 •	48 •	50 •	43 ••	77 ••	170 •••	223 •••	378 •••	589 •••	645 ••••	673 ••••	699 ••••
1280x720 @ 2 FPS	62 •	64 •	60 •	60 •	68 •	116 •	199 ••	311 •••	520 •••	626 •••	1090 •••	1314 ••••	1229 ••••
1280x720 @ 5 FPS	143 •	146 •	149 •	149 •	145 •	161 •	226 •••	370 •••	536 •••	691 •••	1080 •••	2323 •••	2489 ••••
1280x720 @ 15 FPS	280 •	293 •	296 •	294 •	276 •	295 •	319 ••	487 ••	512 •••	639 •••	1360 •••	2237 •••	4413 •••
1280x720 @ 30 FPS	388 •	409 •	411 •	388 •	393 •	398 •	405 •	638 •	857 ••	851 ••	1198 •••	2481 •••	5257 •••
1920x1080 @ 1 FPS	117 •	122 •	119 •	119 •	116 •	101 •	148 •••	315 •••	433 •••	545 ••••	869 •	1763 ••••	1790 ••••
1920x1080 @ 2 FPS	146 •	143 •	144 •	136 •	140 •	147 •	239 •	374 ••	403 •••	731 •••	1294 •••	2567 ••	3226 ••••
1920x1080 @ 5 FPS	323 •	328 •	338 •	347 •	333 •	340 •	349 •	480 ••	613 •••	719 •••	1472 •••	2582 •••	5908 •••
1920x1080 @ 15 FPS	738 •	719 •	721 •	735 •	735 •	736 •	660 •	739 •	835 •	1056 ••	1329 •••	2590 •••	5220 •••
1920x1080 @ 30 FPS	1047 •	1017 •	1049 •	1051 •	1049 •	1002 •	986 •	979 •	1094 •	1224 •	2022 ••	2472 •••	5160 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R	: $R \in [0, R_{targ}]$
R	: $R \in (R_{targ}, R_{max}]$
R	: $R \in (R_{max}, \infty)$
••••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	: $F_r \div F_e \geq 90\%$ for R_{100}
•	: $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h264 main abr
GOP Mode: 30 f
Compression: 30
ZS Strength: off

Figure B.1: Stream quality analysis for Axis Q8752-E Baseline (H.264 Main ABR) test

	9.6 7	14.4 11	28.8 23	33.6 26	56 44	128 102	256 204	512 409	768 614	1000 800	2000 1600	4000 3200	8000 6400
	R_{nom}, R_{max} (kbps)												
320x180 @ 1 FPS	7 •	8 •	17 •	20 •	34 •••	56 ••••	55 ••••	53 ••••	54 ••••	53 ••••	51 ••••	53 ••••	52 ••••
320x180 @ 2 FPS	9 •	13 •	17 ••	21 •	37 •••	91 •••	95 ••••	86 ••••	92 ••••	92 ••••	91 ••••	89 ••••	90 ••••
320x180 @ 5 FPS	11 •	14 •	21 ••	24 ••	38 •••	102 •••	157 •••	179 ••••	173 ••••	174 ••••	175 ••••	164 ••••	174 ••••
320x180 @ 15 FPS	20 •	24 •	37 •	38 •	47 ••	78 •••	173 •••	321 •••	402 •••	422 ••••	434 ••••	395 ••••	428 ••••
320x180 @ 30 FPS	34 •	34 •	42 •	49 •	70 •	84 •••	154 •••	317 •••	477 •••	583 •••	666 ••••	716 ••••	704 ••••
480x270 @ 1 FPS	9 •	10 •	15 ••	22 •	35 ••	78 ••	95 ••••	96 ••••	97 ••••	93 ••••	94 ••••	96 ••••	99 ••••
480x270 @ 2 FPS	11 •	15 •	21 •	25 •	37 •••	85 •••	163 •••	158 ••••	160 ••••	164 ••••	165 ••••	162 ••••	160 ••••
480x270 @ 5 FPS	20 •	22 •	28 •	30 •	36 •••	85 •••	184 •••	275 •••	301 ••••	295 ••••	291 ••••	298 ••••	294 ••••
480x270 @ 15 FPS	38 •	38 •	43 •	45 •	64 •	86 •••	159 •••	316 •••	508 •••	579 •••	709 ••••	706 ••••	671 ••••
480x270 @ 30 FPS	60 •	61 •	60 •	65 •	80 •	138 •	145 •••	294 •••	451 •••	634 •••	1020 •••	1130 ••••	1149 ••••
800x450 @ 1 FPS	24 •	23 •	24 •	26 •	36 •	73 •	146 •••	285 •••	276 ••••	278 ••••	279 ••••	284 ••••	280 ••••
800x450 @ 2 FPS	25 •	26 •	29 •	32 •	46 •	78 ••	165 •••	349 •••	504 •••	501 ••••	509 ••••	496 ••••	494 ••••
800x450 @ 5 FPS	57 •	56 •	59 •	56 •	68 •	95 ••	173 •••	366 •••	547 •••	678 •••	915 ••••	889 ••••	905 ••••
800x450 @ 15 FPS	106 •	107 •	104 •	94 •	110 •	152 •	211 ••	322 •••	516 •••	639 •••	1383 •••	2039 ••••	2134 ••••
800x450 @ 30 FPS	160 •	158 •	160 •	153 •	171 •	179 •	311 •	358 •••	438 •••	589 •••	1227 •••	2647 •••	3258 ••••
1280x720 @ 1 FPS	59 •	59 •	59 •	60 •	88 •	73 •	139 •••	310 •••	462 •••	725 •••	735 ••••	723 ••••	740 ••••
1280x720 @ 2 FPS	63 •	64 •	61 •	66 •	70 •	106 •	160 ••	352 •••	513 •••	710 •••	1332 •••	1291 ••••	1363 ••••
1280x720 @ 5 FPS	152 •	147 •	141 •	142 •	151 •	173 •	208 •	356 •••	543 •••	679 •••	1463 •••	2418 •••	2590 ••••
1280x720 @ 15 FPS	287 •	281 •	291 •	288 •	277 •	289 •	332 •	500 •	507 •••	613 •••	1232 •••	2793 •••	5064 •••
1280x720 @ 30 FPS	417 •	423 •	411 •	409 •	284 •	428 •	426 •	645 •	852 •	881 ••	1165 •••	2429 •••	5030 •••
1920x1080 @ 1 FPS	141 •	137 •	144 •	141 •	205 •	117 •	173 •	297 •	451 •••	593 •	1390 •••	1853 ••••	1867 ••••
1920x1080 @ 2 FPS	150 •	144 •	153 •	148 •	151 •	152 •	229 •	356 •	532 •••	471 ••••	1286 •••	2888 •••	3592 ••••
1920x1080 @ 5 FPS	357 •	338 •	348 •	339 •	347 •	342 •	342 •	489 •	620 •	721 ••	1416 •••	2924 •••	5786 •••
1920x1080 @ 15 FPS	733 •	761 •	726 •	750 •	738 •	749 •	721 •	755 •	886 ••	1046 ••	1340 •••	2860 •••	5895 •••
1920x1080 @ 30 FPS	1060 •	1070 •	1063 •	1020 •	692 •	1038 •	1020 •	1041 •	1131 •	1276 ••	1971 ••	2442 •••	5453 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R (green) : $R \in [0, R_{max}]$
R (red) : $R \in (m, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h264 main mbr
GOP Mode: 30 f
Compression: 30
ZS Strength: off

Figure B.2: Stream quality analysis for Axis Q8752-E MBR Rate Control test

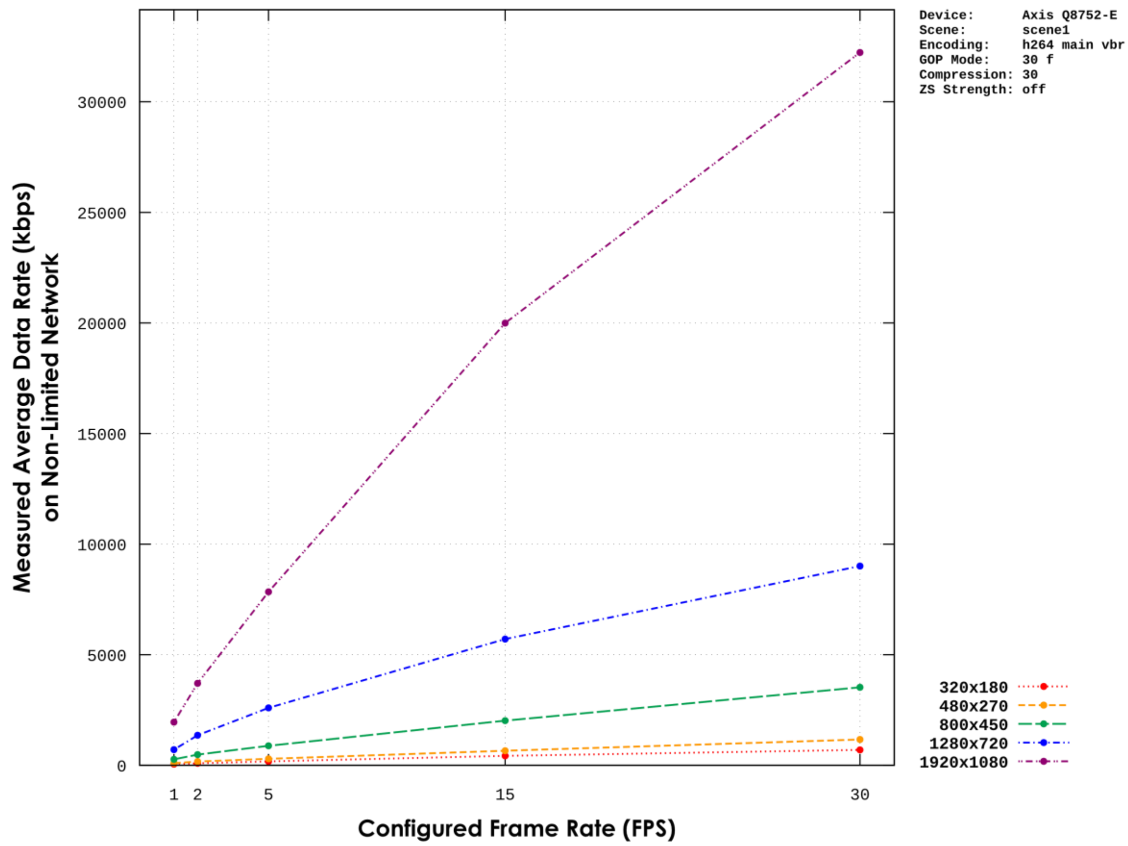

Figure B.3: Average bitrates for Axis Q8752-E VBR Rate Control test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	6 •	9 ••	18 ••	19 •••	26 •	43 ••••	43 ••••	46 ••••	45 ••••	41 ••••	45 ••••	43 ••••	46 ••••
320x180 @ 2 FPS	9 •	12 •	16 •••	19 •••	37 •••	78 •••	76 ••••	72 ••••	75 ••••	73 ••••	77 ••••	78 ••••	74 ••••
320x180 @ 5 FPS	12 •	15 •	23 ••	24 •••	38 •••	77 •••	141 •••	142 ••••	143 ••••	141 ••••	132 ••••	139 ••••	139 ••••
320x180 @ 15 FPS	22 •	22 •	36 •	37 •	49 •	86 •••	153 •••	294 •••	368 ••••	310 ••••	347 ••••	357 ••••	352 ••••
320x180 @ 30 FPS	35 •	36 •	43 •	46 •	68 •	86 •••	159 •••	307 •••	432 •••	509 •••	534 ••••	537 ••••	556 ••••
480x270 @ 1 FPS	7 •	10 •	19 •	24 •	32 •••	72 ••	79 ••••	81 ••••	81 ••••	83 ••••	79 ••••	81 ••••	80 ••••
480x270 @ 2 FPS	9 •	16 •	20 •	27 ••	37 •••	78 •••	143 •••	141 ••••	128 ••••	131 ••••	134 ••••	138 ••••	133 ••••
480x270 @ 5 FPS	20 •	23 •	29 •	30 •	40 •••	87 •••	141 •••	230 ••••	247 ••••	253 ••••	258 ••••	238 ••••	235 ••••
480x270 @ 15 FPS	41 •	40 •	48 •	44 •	66 •	90 •••	165 •••	329 •••	516 •••	571 •••	537 ••••	594 ••••	571 ••••
480x270 @ 30 FPS	63 •	64 •	65 •	64 •	82 •	142 •	155 •••	314 •••	439 •••	619 •••	915 ••••	1008 ••••	931 ••••
800x450 @ 1 FPS	21 •	21 •	21 •	25 •	35 ••	85 ••••	132 •••	232 ••••	230 ••••	229 ••••	243 ••••	219 ••••	234 ••••
800x450 @ 2 FPS	24 •	25 •	31 •	31 •	46 •	93 •••	179 •••	360 •••	430 •••	401 ••••	409 ••••	408 ••••	412 ••••
800x450 @ 5 FPS	56 •	59 •	59 •	59 •	69 •	100 ••	173 •••	330 •••	415 •••	620 •••	760 ••••	769 ••••	592 ••••
800x450 @ 15 FPS	111 •	114 •	116 •	116 •	113 •	152 •	221 ••	313 •••	516 •••	677 •••	1293 •••	1720 ••••	1677 ••••
800x450 @ 30 FPS	169 •	174 •	172 •	175 •	173 •	188 •	315 •	387 •••	446 •••	602 •••	1211 •••	2366 •••	2996 ••••
1280x720 @ 1 FPS	51 •	52 •	52 •	50 •	46 •	73 •••	198 •••	291 •••	374 ••	534 •••	621 ••••	565 ••••	583 ••••
1280x720 @ 2 FPS	65 •	62 •	66 •	63 •	75 •	121 •	166 ••	352 •••	495 •••	593 •••	1082 •••	1122 ••••	1045 ••••
1280x720 @ 5 FPS	157 •	159 •	151 •	150 •	149 •	171 •	238 ••	362 •••	536 •••	681 •••	1337 •••	2249 •••	1755 ••••
1280x720 @ 15 FPS	313 •	314 •	305 •	308 •	317 •	315 •	344 •	528 •	606 •••	645 •••	1415 •••	2409 •••	4536 •••
1280x720 @ 30 FPS	429 •	450 •	436 •	448 •	451 •	458 •	433 •	636 •	866 •	974 ••	1237 •••	2603 •••	5004 •••
1920x1080 @ 1 FPS	120 •	124 •	122 •	119 •	126 •	124 •	163 •••	376 •••	397 •••	572 ••••	894 ••	1619 ••••	1455 ••••
1920x1080 @ 2 FPS	146 •	152 •	154 •	153 •	152 •	162 •	245 •	387 ••	491 •••	585 •••	1316 •••	2260 •••	3108 ••••
1920x1080 @ 5 FPS	356 •	380 •	374 •	367 •	360 •	358 •	354 •	509 ••	643 •••	702 •••	1428 •••	2702 •••	5072 •••
1920x1080 @ 15 FPS	812 •	800 •	796 •	793 •	810 •	792 •	771 •	776 •	905 •	1047 •	1420 •••	2749 •••	5107 •••
1920x1080 @ 30 FPS	1165 •	1178 •	1171 •	1155 •	1178 •	1130 •	1156 •	1099 •	1156 •	1279 •	2116 ••	2545 •••	5371 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0, R_{targ}]$
R : $R \in (R_{targ}, R_{max}]$
R : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h264 high abr
GOP Mode: 30 f
Compression: 30
ZS Strength: off

Figure B.4: Stream quality analysis for Axis Q8752-E H.264 High Profile test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	6 •	10 •	16 •	18 ••	27 •	38 ••••	40 ••••	41 ••••	41 ••••	38 ••••	39 ••••	39 ••••	38 ••••
320x180 @ 2 FPS	8 •	12 •	20 ••	21 •••	33 •••	65 •••	68 ••••	66 ••••	75 ••••	70 ••••	69 ••••	64 ••••	68 ••••
320x180 @ 5 FPS	11 •	14 •	20 ••	22 •••	38 •••	79 •••	125 •••	128 ••••	129 ••••	126 ••••	128 ••••	127 ••••	132 ••••
320x180 @ 15 FPS	19 •	22 •	34 •	37 •	42 ••	80 •••	169 •••	259 •••	286 ••••	300 ••••	305 ••••	295 ••••	288 ••••
320x180 @ 30 FPS	31 •	33 •	41 •	45 •	63 •	83 •••	158 •••	316 •••	412 •••	485 •••	528 ••••	483 ••••	540 ••••
480x270 @ 1 FPS	7 •	10 •	20 •	20 •••	36 •••	74 •••	71 ••••	70 ••••	69 ••••	72 ••••	74 ••••	73 ••••	73 ••••
480x270 @ 2 FPS	9 •	15 •	24 •	25 ••	27 •••	93 •••	121 ••••	115 ••••	121 ••••	126 ••••	122 ••••	127 ••••	124 ••••
480x270 @ 5 FPS	18 •	19 •	28 •	29 •	40 •••	95 •••	181 •••	229 ••••	227 ••••	212 ••••	232 ••••	228 ••••	201 ••••
480x270 @ 15 FPS	34 •	34 •	39 •	40 •	63 •	82 •••	158 •••	306 •••	445 •••	468 •••	485 ••••	494 ••••	492 ••••
480x270 @ 30 FPS	55 •	54 •	54 •	57 •	74 •	121 ••	156 •••	312 •••	471 •••	580 •••	749 ••••	751 ••••	846 ••••
800x450 @ 1 FPS	19 •	18 •	23 •	24 •	34 •	82 ••••	134 ••	199 ••••	207 ••••	190 ••••	197 ••••	188 ••••	194 ••••
800x450 @ 2 FPS	20 •	21 •	27 •	35 •	41 •	75 •••	146 •••	228 •••	325 ••••	327 ••••	347 ••••	317 ••••	329 ••••
800x450 @ 5 FPS	45 •	44 •	47 •	47 •	60 •	87 •••	169 •••	327 •••	396 •••	592 •••	599 ••••	656 ••••	631 ••••
800x450 @ 15 FPS	90 •	91 •	90 •	89 •	89 •	138 ••	198 •••	325 •••	500 •••	602 •••	1206 •••	1510 ••••	1505 ••••
800x450 @ 30 FPS	139 •	143 •	146 •	145 •	144 •	165 •	288 •	330 •••	466 •••	610 •••	1206 •••	2337 •••	2583 ••••
1280x720 @ 1 FPS	44 •	43 •	47 •	48 •	45 •	72 ••	162 •••	253 •••	303 •••	557 •••	562 ••••	518 ••••	570 ••••
1280x720 @ 2 FPS	50 •	51 •	51 •	49 •	59 •	96 •	179 •••	259 •••	431 •••	731 •••	899 •••	912 ••••	975 ••••
1280x720 @ 5 FPS	104 •	114 •	113 •	119 •	114 •	144 •	214 ••	303 •••	505 •••	618 •••	1133 •••	1887 ••••	1910 ••••
1280x720 @ 15 FPS	231 •	227 •	234 •	236 •	237 •	232 •	295 •	464 ••	496 •••	632 •••	1329 •••	2327 •••	4328 •••
1280x720 @ 30 FPS	356 •	340 •	348 •	348 •	331 •	358 •	354 •	607 •	739 ••	768 •••	1223 •••	2679 •••	4912 •••
1920x1080 @ 1 FPS	111 •	111 •	114 •	115 •	117 •	115 •	153 ••	302 •••	435 ••••	630 •••	1249 •••	1443 ••••	1517 ••••
1920x1080 @ 2 FPS	110 •	119 •	116 •	123 •	119 •	137 •	196 •	315 •••	552 •••	484 •••	1228 •••	2216 •••	2788 ••••
1920x1080 @ 5 FPS	283 •	270 •	286 •	278 •	273 •	268 •	296 •	462 ••	534 •••	679 •••	1393 •••	2957 •••	5703 •••
1920x1080 @ 15 FPS	617 •	566 •	592 •	556 •	556 •	580 •	568 •	623 •	806 ••	928 •	1330 •••	2814 •••	5948 •••
1920x1080 @ 30 FPS	876 •	917 •	899 •	902 •	921 •	801 •	913 •	912 •	955 •	1092 ••	1716 ••	2600 •••	5522 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R (green) : $R \in [0, R_{targ}]$
R (yellow) : $R \in (R_{targ}, R_{max}]$
R (red) : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h265 None abr
GOP Mode: 30 f
Compression: 30
ZS Strength: off

Figure B.5: Stream quality analysis for Axis Q8752-E H.265 Main Profile test

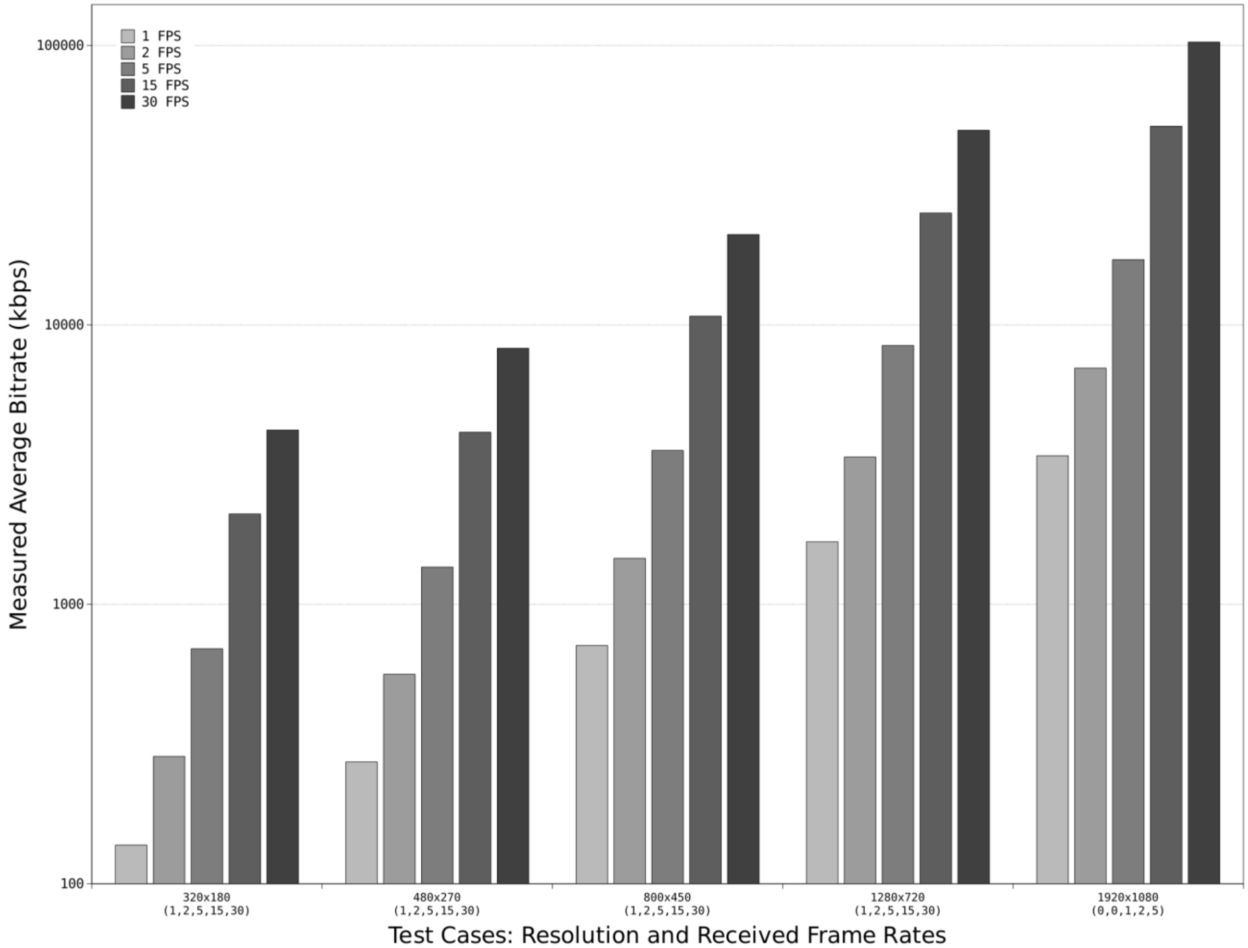

Figure B.6: Average bitrates for Axis Q8752-E M-JPEG test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	10 •	15 •	23 •••	24 •••	30 ••	55 ••••	60 ••••	60 ••••	61 ••••	62 ••••	61 ••••	62 ••••	63 ••••
320x180 @ 2 FPS	11 •	14 •	17 •••	22 •••	37 •••	84 •••	97 ••••	96 ••••	98 ••••	94 ••••	96 ••••	94 ••••	88 ••••
320x180 @ 5 FPS	12 •	15 •	20 •	23 •••	35 •••	91 •••	144 •••	156 ••••	158 ••••	154 ••••	148 ••••	157 ••••	156 ••••
320x180 @ 15 FPS	17 •	19 •	28 •	30 •	40 ••	92 •••	143 •••	282 •••	336 •••	357 ••••	343 ••••	381 ••••	391 ••••
320x180 @ 30 FPS	24 •	24 •	34 •	35 •	51 •	95 •••	160 •••	371 •••	497 •••	509 •••	547 ••••	598 ••••	496 ••••
480x270 @ 1 FPS	16 •	16 •	27 •	29 ••	45 •••	61 •	91 ••	108 ••••	108 ••••	110 ••••	108 ••••	109 ••••	112 ••••
480x270 @ 2 FPS	14 •	20 •	28 •	27 •	39 •••	80 •••	148 •••	171 ••••	168 ••••	167 ••••	175 ••••	168 ••••	171 ••••
480x270 @ 5 FPS	22 •	22 •	29 •	32 •	40 ••	82 •••	133 •••	273 •••	279 ••••	268 ••••	255 ••••	288 ••••	256 ••••
480x270 @ 15 FPS	33 •	32 •	36 •	36 •	52 •	87 •••	188 •••	278 •••	447 •••	527 •••	589 ••••	547 ••••	562 ••••
480x270 @ 30 FPS	46 •	46 •	47 •	48 •	61 •	103 •••	190 •••	327 •••	410 •••	615 •••	941 •••	859 ••••	965 ••••
800x450 @ 1 FPS	41 •	41 •	42 •	43 •	54 •	89 •••	120 ••	238 •••	310 ••••	289 ••••	303 ••••	295 ••••	308 ••••
800x450 @ 2 FPS	37 •	37 •	40 •	43 •	55 •	96 •••	168 •••	276 •••	450 •••	498 •••	499 ••••	492 ••••	520 ••••
800x450 @ 5 FPS	62 •	62 •	61 •	64 •	67 •	104 ••	159 •••	338 •••	400 •••	427 •••	841 ••••	841 ••••	790 ••••
800x450 @ 15 FPS	95 •	88 •	94 •	89 •	94 •	123 ••	180 •••	383 •••	548 •••	654 •••	1246 •••	1660 ••••	1759 ••••
800x450 @ 30 FPS	123 •	121 •	129 •	124 •	128 •	142 •	212 ••	365 •••	568 •••	750 •••	1102 •••	2304 •••	3040 ••••
1280x720 @ 1 FPS	89 •	90 •	86 •	89 •	86 •	103 ••	162 •••	319 •••	375 •	392 •	750 ••••	822 ••••	771 ••••
1280x720 @ 2 FPS	86 •	84 •	87 •	87 •	94 •	131 •	197 •	356 •••	518 •••	635 •••	1232 •••	1245 ••••	1365 ••••
1280x720 @ 5 FPS	161 •	153 •	160 •	153 •	158 •	159 •	240 ••	335 •••	520 •••	669 •••	1125 •••	2350 •••	2271 ••••
1280x720 @ 15 FPS	264 •	262 •	253 •	259 •	259 •	263 •	291 •	402 •••	555 •••	698 •••	1492 •••	2244 •••	4636 •••
1280x720 @ 30 FPS	344 •	342 •	346 •	325 •	345 •	330 •	349 •	484 ••	598 •••	733 •••	1452 •••	2683 •••	5847 •••
1920x1080 @ 1 FPS	192 •	186 •	191 •	186 •	190 •	196 •	221 •	341 •••	440 ••••	554 •••	931 •••	1975 ••••	1921 ••••
1920x1080 @ 2 FPS	187 •	189 •	192 •	194 •	172 •	199 •	219 •	459 •••	455 •••	574 •••	1441 •••	2024 •••	3427 ••••
1920x1080 @ 5 FPS	364 •	374 •	359 •	348 •	363 •	305 •	373 ••	493 ••	605 •••	702 •••	1447 •••	2584 •••	5266 •••
1920x1080 @ 15 FPS	681 •	662 •	668 •	649 •	529 •	632 •	692 •	669 ••	804 •	915 ••	1489 •••	2614 •••	5552 •••
1920x1080 @ 30 FPS	904 •	874 •	920 •	935 •	632 •	908 •	911 •	797 •	956 •	1014 ••	1640 •••	2914 •••	5517 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R (green) : $R \in [0, R_{targ}]$
R (yellow) : $R \in (R_{targ}, R_{max}]$
R (red) : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h264 main abr
GOP Mode: 5 s
Compression: 30
ZS Strength: off

Figure B.7: Stream quality analysis for Axis Q8752-E Varying GOP Interval with Frame Rate test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	5 •	5 •	5 •••	5 •••	6 ••••	5 ••••	6 ••••	5 ••••	6 ••••	6 ••••	5 ••••	5 ••••	6 ••••
320x180 @ 2 FPS	7 •	8 •	9 ••	9 •••	9 ••••	8 ••••	8 ••••	9 ••••	9 ••••	8 ••••	9 ••••	8 ••••	9 ••••
320x180 @ 5 FPS	9 •	11 •	15 •	15 ••	15 •••	15 ••••	15 ••••	15 ••••	15 ••••	15 ••••	15 ••••	15 ••••	15 ••••
320x180 @ 15 FPS	14 •	20 •	24 •	26 ••	31 •••	33 ••••	30 ••••	33 ••••	34 ••••	33 ••••	33 ••••	33 ••••	33 ••••
320x180 @ 30 FPS	20 •	24 •	40 •	41 •	43 ••	56 ••••	56 ••••	58 ••••	56 ••••	57 ••••	55 ••••	56 ••••	57 ••••
480x270 @ 1 FPS	5 •	8 •	11 ••	11 ••	11 ••••	11 ••••	10 ••••	11 ••••	11 ••••	10 ••••	11 ••••	11 ••••	11 ••••
480x270 @ 2 FPS	9 •	11 •	17 ••	18 ••	17 •••	17 ••••	18 ••••	18 ••••	17 ••••	18 ••••	17 ••••	17 ••••	17 ••••
480x270 @ 5 FPS	12 •	15 •	22 •	22 ••	27 •••	28 ••••	27 ••••	28 ••••	28 ••••	27 ••••	28 ••••	28 ••••	28 ••••
480x270 @ 15 FPS	21 •	25 •	35 •	39 •	47 ••	58 •••	63 ••••	62 ••••	60 ••••	61 ••••	63 ••••	61 ••••	63 ••••
480x270 @ 30 FPS	34 •	35 •	46 •	51 •	71 •	81 •••	100 ••••	102 ••••	96 ••••	104 ••••	100 ••••	102 ••••	100 ••••
800x450 @ 1 FPS	8 •	9 •	17 •	14 •	29 ••	32 ••••	29 ••••	31 ••••	30 ••••	30 ••••	29 ••••	30 ••••	30 ••••
800x450 @ 2 FPS	15 •	17 •	26 •	28 •	42 ••	47 ••••	50 ••••	49 ••••	52 ••••	48 ••••	52 ••••	48 ••••	49 ••••
800x450 @ 5 FPS	29 •	28 •	37 •	38 •	48 ••	74 •••	76 ••••	79 ••••	78 ••••	76 ••••	79 ••••	75 ••••	76 ••••
800x450 @ 15 FPS	58 •	58 •	58 ••	58 •	72 •	117 ••	149 •••	161 ••••	157 ••••	160 ••••	157 ••••	162 ••••	157 ••••
800x450 @ 30 FPS	86 •	83 •	86 •	87 •	95 ••	162 •	189 •••	252 ••••	258 ••••	262 ••••	254 ••••	263 ••••	265 ••••
1280x720 @ 1 FPS	18 •	17 •	23 ••	23 ••	32 •	75 •••	74 ••••	81 ••••	73 ••••	75 ••••	72 ••••	76 ••••	76 ••••
1280x720 @ 2 FPS	34 •	36 •	37 •	40 •	58 •	97 •••	126 •••	135 ••••	134 ••••	134 ••••	126 ••••	135 ••••	134 ••••
1280x720 @ 5 FPS	81 •	79 •	81 •	79 •	78 •	118 ••	109 •••	218 ••••	207 ••••	220 ••••	206 ••••	214 ••••	217 ••••
1280x720 @ 15 FPS	156 •	162 •	154 •	161 •	166 •	179 •	273 ••	315 •••	399 •••	399 ••••	395 ••••	409 ••••	395 ••••
1280x720 @ 30 FPS	216 •	224 •	231 •	212 •	221 •	232 •	325 •	433 ••	470 •••	531 ••••	640 ••••	614 ••••	627 ••••
1920x1080 @ 1 FPS	42 •	42 •	42 •	41 •	48 •	82 •••	111 •••	186 ••••	169 ••••	176 ••••	166 ••••	162 ••••	159 ••••
1920x1080 @ 2 FPS	76 •	80 •	80 •	74 •	77 •	122 ••	194 •••	308 •••	299 ••••	290 ••••	305 ••••	308 ••••	306 ••••
1920x1080 @ 5 FPS	177 •	191 •	142 •	172 •	189 •	190 •	247 ••	378 •••	464 •••	513 •••	534 ••••	549 ••••	515 ••••
1920x1080 @ 15 FPS	406 •	382 •	395 •	376 •	301 •	377 •	403 •	542 ••	688 ••	702 •••	962 ••••	966 ••••	998 ••••
1920x1080 @ 30 FPS	579 •	579 •	563 •	580 •	561 •	574 •	519 •••	661 ••••	903 •	1037 ••	1141 •••	1475 ••••	1464 ••••

R	:	measured average bitrate (kbps)
R_{nom}	:	nominal bitrate for link class (kbps)
R_{100}	:	net-limit test rate (100% of R_{nom})
R_{80}	:	net-limit test rate (80% of R_{nom})
R_{50}	:	net-limit test rate (50% of R_{nom})
R_{max}	:	specified max. rate (80% of R_{nom})
R_{targ}	:	specified target rate (80% of R_{max})
F_r	:	# frames received
F_e	:	# frames expected

R	:	$R \in [0, R_{targ}]$
R	:	$R \in (R_{targ}, R_{max}]$
R	:	$R \in (R_{max}, \infty)$
••••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	:	$F_r \div F_e \geq 90\%$ for R_{100}
•	:	$F_r \div F_e \geq 90\%$ for no test rates

Device:	Axis Q8752-E
Scene:	scene1
Encoding:	h264 main abr
GOP Mode:	30 f
Compression:	100
ZS Strength:	off

Figure B.8: Stream quality analysis for Axis Q8752-E Compression 100 test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	6 •	9 •	16 ••	16 ••	24 •	40 ••••	40 ••••	37 ••••	38 ••••	33 ••••	39 ••••	38 ••••	41 ••••
320x180 @ 2 FPS	9 •	12 •	20 ••	20 ••	41 •••	63 •••	64 ••••	67 ••••	71 ••••	63 ••••	65 ••••	65 ••••	64 ••••
320x180 @ 5 FPS	12 •	16 •	19 ••	31 •••	50 •••	85 •••	106 ••••	98 ••••	97 ••••	96 ••••	103 ••••	99 ••••	98 ••••
320x180 @ 15 FPS	19 •	24 •	39 •	33 •	38 •••	78 •••	152 •••	227 •••	188 ••••	237 ••••	239 ••••	230 ••••	260 ••••
320x180 @ 30 FPS	27 •	31 •	49 •	53 •	55 •	76 •••	146 •••	288 •••	308 •••	371 ••••	382 ••••	391 ••••	417 ••••
480x270 @ 1 FPS	7 •	10 •	18 ••	20 •••	30 ••••	67 •••	66 ••••	70 ••••	66 ••••	77 ••••	75 ••••	72 ••••	72 ••••
480x270 @ 2 FPS	11 •	15 •	22 •	25 ••	34 ••	85 •••	110 •••	119 ••••	128 ••••	131 ••••	121 ••••	121 ••••	122 ••••
480x270 @ 5 FPS	18 •	19 •	32 •	35 ••	44 •••	70 •••	169 •••	195 ••••	171 ••••	179 ••••	192 ••••	198 ••••	181 ••••
480x270 @ 15 FPS	28 •	33 •	42 •	45 •	62 •	76 •••	150 •••	291 •••	403 •••	333 ••••	454 ••••	406 ••••	446 ••••
480x270 @ 30 FPS	49 •	52 •	57 •	61 •	87 •	111 ••	144 •••	290 •••	415 •••	522 •••	713 ••••	761 ••••	696 ••••
800x450 @ 1 FPS	17 •	17 •	20 •	22 •	35 •••	73 •••	111 •••	222 ••••	207 ••••	212 ••••	215 ••••	202 ••••	210 ••••
800x450 @ 2 FPS	21 •	23 •	33 •	35 •	47 •	74 •••	172 •••	329 •••	372 •••	384 ••••	339 ••••	380 ••••	381 ••••
800x450 @ 5 FPS	45 •	47 •	56 •	56 •	62 ••	88 •••	159 •••	345 •••	496 •••	557 •••	588 ••••	605 ••••	563 ••••
800x450 @ 15 FPS	88 •	90 •	89 •	85 •	92 •	150 •	154 •••	312 •••	464 •••	643 •••	1152 •••	1296 ••••	1407 ••••
800x450 @ 30 FPS	128 •	132 •	128 •	128 •	134 •	183 •	270 •	313 •••	429 •••	569 •••	1209 •••	2081 •••	2081 ••••
1280x720 @ 1 FPS	43 •	45 •	44 •	44 •	45 ••	80 •••	148 ••••	268 •••	325 •••	531 •••	534 ••••	577 ••••	534 ••••
1280x720 @ 2 FPS	57 •	58 •	55 •	55 •	74 •	103 ••	181 •••	296 •••	478 •••	513 •••	1050 •••	1015 ••••	1046 ••••
1280x720 @ 5 FPS	121 •	125 •	122 •	125 •	127 •	142 •	218 •••	355 •••	555 •••	711 •••	1288 •••	1836 ••••	1699 ••••
1280x720 @ 15 FPS	242 •	258 •	245 •	247 •	254 •	255 •	312 •	434 ••	470 •••	604 •••	1301 •••	2277 •••	3929 •••
1280x720 @ 30 FPS	352 •	362 •	335 •	346 •	337 •	340 ••	391 ••	640 •	742 ••	711 •••	1154 •••	2439 •••	4923 •••
1920x1080 @ 1 FPS	105 •	104 •	101 •	104 •	69 •	128 ••	152 ••	326 •••	437 •••	538 •••	1157 •••	1542 ••••	1415 ••••
1920x1080 @ 2 FPS	130 •	130 •	124 •	120 •	124 •	152 •	210 ••	306 ••	521 •••	557 •••	1204 •••	2437 •••	2790 ••••
1920x1080 @ 5 FPS	303 •	302 •	293 •	280 •	309 •	209 •	340 ••	382 ••	637 •••	714 •••	1527 •••	3031 •••	4620 •••
1920x1080 @ 15 FPS	651 •	645 •	641 •	613 •	651 •	638 •	431 •	708 •	854 ••	968 ••	1238 •••	2784 •••	4796 •••
1920x1080 @ 30 FPS	918 •	881 •	921 •	884 •	596 •	582 •	893 •	872 •	1048 •	1219 •	1722 ••	2359 •••	4796 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0, R_{targ}]$
R : $R \in (R_{targ}, R_{max}]$
R : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h264 main abr
GOP Mode: 30 f
Compression: 30
ZS Strength: 10

Figure B.9: Stream quality analysis for Axis Q8752-E Zipstream Strength 10 test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	5 •	8 ••	13 ••	18 ••	33 •	33 ••••	31 ••••	33 ••••	33 ••••	34 ••••	32 ••••	32 ••••	32 ••••
320x180 @ 2 FPS	9 •	11 •	19 ••	20 ••	29 ••	55 ••••	54 ••••	53 ••••	52 ••••	55 ••••	53 ••••	57 ••••	53 ••••
320x180 @ 5 FPS	12 •	12 •	30 •••	34 •••	33 •••	68 •••	76 ••••	78 ••••	76 ••••	72 ••••	75 ••••	71 ••••	75 ••••
320x180 @ 15 FPS	20 •	27 •	29 •	31 •	39 •••	73 •••	141 •••	187 ••••	187 ••••	167 ••••	169 ••••	172 ••••	182 ••••
320x180 @ 30 FPS	26 •	32 •	49 •	52 •	56 •	81 •••	143 •••	255 •••	303 ••••	311 ••••	293 ••••	295 ••••	296 ••••
480x270 @ 1 FPS	7 •	10 •	18 •••	17 •••	27 ••	61 •••	63 ••••	65 ••••	63 ••••	64 ••••	62 ••••	61 ••••	64 ••••
480x270 @ 2 FPS	12 •	14 •	23 ••	22 •	36 •••	67 •••	111 ••••	111 ••••	112 ••••	103 ••••	106 ••••	105 ••••	102 ••••
480x270 @ 5 FPS	16 •	21 •	30 •	26 •	42 •••	72 •••	131 •••	143 ••••	142 ••••	149 ••••	148 ••••	147 ••••	145 ••••
480x270 @ 15 FPS	27 •	30 •	43 •	50 •	56 •	75 •••	143 •••	274 •••	338 ••••	351 ••••	324 ••••	345 ••••	352 ••••
480x270 @ 30 FPS	45 •	46 •	55 •	58 •	83 •	102 ••	145 •••	282 •••	399 •••	480 •••	592 ••••	601 ••••	540 ••••
800x450 @ 1 FPS	17 •	16 •	20 •	20 •	34 •••	72 •••	139 •••	187 ••••	179 ••••	184 ••••	192 ••••	176 ••••	176 ••••
800x450 @ 2 FPS	26 •	27 •	30 •	36 •	41 •	89 •••	170 •••	320 •••	345 ••••	351 ••••	322 ••••	324 ••••	347 ••••
800x450 @ 5 FPS	43 •	41 •	50 •	50 •	58 •	92 •••	175 •••	282 •••	445 •••	494 •••	493 ••••	499 ••••	485 ••••
800x450 @ 15 FPS	79 •	80 •	81 •	81 •	93 •	145 •	163 •••	292 •••	470 •••	626 •••	982 •••	1017 ••••	1108 ••••
800x450 @ 30 FPS	112 •	115 •	114 •	116 •	127 •	187 •	268 ••	297 •••	414 •••	547 •••	1111 •••	1886 ••••	1927 ••••
1280x720 @ 1 FPS	43 •	44 •	44 •	42 •	44 •	81 ••	167 •••	280 •••	306 •	478 •••	496 ••••	490 ••••	483 ••••
1280x720 @ 2 FPS	69 •	68 •	68 •	70 •	75 •	107 •	177 •••	315 •••	482 ••	685 ••	905 ••••	899 ••••	933 ••••
1280x720 @ 5 FPS	124 •	118 •	123 •	116 •	114 •	143 •	217 ••	355 •••	575 •••	620 •••	1210 •••	1488 ••••	1474 ••••
1280x720 @ 15 FPS	235 •	228 •	233 •	235 •	233 •	237 •	305 •	394 •••	462 •••	599 •••	1271 •••	2193 •••	3219 ••••
1280x720 @ 30 FPS	322 •	314 •	307 •	300 •	311 •	311 •	385 •	611 •	681 ••	667 •••	1155 •••	2423 •••	4531 •••
1920x1080 @ 1 FPS	105 •	104 •	106 •	108 •	107 •	103 •	158 ••	302 •••	481 •••	578 •••	1142 •••	1331 ••••	1256 ••••
1920x1080 @ 2 FPS	166 •	161 •	158 •	164 •	162 •	164 •	242 •	388 ••	522 •••	582 •••	1292 •••	2382 •••	2393 ••••
1920x1080 @ 5 FPS	295 •	292 •	290 •	295 •	285 •	288 •	316 •	408 ••	564 •••	735 •••	1507 •••	2346 •••	4369 •••
1920x1080 @ 15 FPS	577 •	563 •	588 •	562 •	589 •	571 •	545 •	685 •	823 •	946 ••	1159 •••	2675 •••	4354 •••
1920x1080 @ 30 FPS	821 •	793 •	812 •	840 •	806 •	837 •	824 •	870 •	1023 •	1227 •	1591 •••	2275 •••	4885 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R (green) : $R \in [0, R_{targ}]$
R (yellow) : $R \in (R_{targ}, R_{max}]$
R (red) : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h264 main abr
GOP Mode: 30 f
Compression: 30
ZS Strength: 30

Figure B.10: Stream quality analysis for Axis Q8752-E Zipstream Strength 30 test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	6 •	8 •	12 •	16 •	24 •••	24 ••••	25 ••••	25 ••••	25 ••••	24 ••••	25 ••••	25 ••••	24 ••••
320x180 @ 2 FPS	8 •	10 ••	21 •••	23 •••	29 •••	42 ••••	42 ••••	39 ••••	41 ••••	43 ••••	43 ••••	34 ••••	42 ••••
320x180 @ 5 FPS	12 •	14 •	24 •••	24 •••	33 •••	50 ••••	54 ••••	52 ••••	56 ••••	57 ••••	53 ••••	56 ••••	57 ••••
320x180 @ 15 FPS	20 •	30 •	27 •	35 ••	41 •••	77 •••	123 ••••	134 ••••	129 ••••	126 ••••	125 ••••	126 ••••	132 ••••
320x180 @ 30 FPS	25 •	35 •	48 •	48 •	55 •	85 •••	148 •••	217 ••••	214 ••••	223 ••••	223 ••••	229 ••••	215 ••••
480x270 @ 1 FPS	14 •	11 •	18 ••	18 •	26 ••	50 •••	51 ••••	52 ••••	54 ••••	50 ••••	50 ••••	54 ••••	50 ••••
480x270 @ 2 FPS	20 •	20 •	21 •	27 •••	41 •••	82 ••	88 ••••	88 ••••	87 ••••	87 ••••	87 ••••	87 ••••	89 ••••
480x270 @ 5 FPS	14 •	19 •	31 •	30 •	48 •	74 •••	112 ••••	111 ••••	112 ••••	119 ••••	111 ••••	117 ••••	120 ••••
480x270 @ 15 FPS	24 •	32 •	45 •	42 •	50 •	90 •••	145 •••	241 •••	276 ••••	266 ••••	265 ••••	277 ••••	265 ••••
480x270 @ 30 FPS	38 •	44 •	54 •	64 •	82 •	102 •••	153 •••	283 •••	360 ••••	425 ••••	473 ••••	353 ••••	443 ••••
800x450 @ 1 FPS	38 •	38 •	37 •	41 •	38 •	69 •••	112 ••	154 ••••	156 ••••	159 ••••	156 ••••	157 ••••	165 ••••
800x450 @ 2 FPS	64 •	65 •	65 •	75 •	68 •	96 •••	165 •••	283 •••	269 ••••	282 ••••	275 ••••	283 ••••	271 ••••
800x450 @ 5 FPS	44 •	48 •	43 •	46 •	55 •	84 •••	154 •••	283 •••	397 •••	388 ••••	397 ••••	395 ••••	401 ••••
800x450 @ 15 FPS	63 •	67 •	71 •	69 •	86 •	166 ••	156 •••	311 •••	446 •••	571 •••	783 ••••	872 ••••	910 ••••
800x450 @ 30 FPS	101 •	101 •	109 •	101 •	119 •	187 •	238 ••	302 •••	458 •••	596 •••	1103 •••	1446 ••••	1450 ••••
1280x720 @ 1 FPS	100 •	97 •	96 •	97 •	100 •	103 •	171 •	313 •••	415 •••	424 •••	413 ••••	421 ••••	470 ••••
1280x720 @ 2 FPS	172 •	177 •	175 •	197 •	195 •	204 •	234 ••	323 •••	424 •••	552 •••	792 ••••	832 ••••	777 ••••
1280x720 @ 5 FPS	151 •	154 •	121 •	141 •	146 •	149 •	217 •••	297 •••	493 •••	574 •••	1161 •••	1229 ••••	1314 ••••
1280x720 @ 15 FPS	206 •	198 •	185 •	200 •	206 •	235 •	291 ••	358 •••	432 •••	575 •••	1258 •••	2150 •••	2756 ••••
1280x720 @ 30 FPS	270 •	274 •	283 •	284 •	280 •	286 •	366 •	577 •	623 •••	618 •••	1184 •••	2353 •••	3845 •••
1920x1080 @ 1 FPS	256 •	261	244 •	261 •	264 •	250 •	258 •	327 •••	490 •••	573 ••	1113 •••	1117 ••••	1105 ••••
1920x1080 @ 2 FPS	498 •	501 •	518 •	502	490 •	478 •	499 •	572 •	588 •	605 •••	1265 •••	2081 ••••	1998 ••••
1920x1080 @ 5 FPS	405 •	391 •	382 •	392 •	348 •	386 •	390 •	446 •	586 ••	716 •••	1239 •••	2534 •••	4071 •••
1920x1080 @ 15 FPS	525 •	506 •	526 •	528 •	515 •	521 •	551 •	665 •	774 ••	909 ••	1262 •••	2543 •••	5369 •••
1920x1080 @ 30 FPS	730 •	763 •	627 •	571 •	769 •	719 •	718 •	824 •	995 •	1172 ••	1414 •••	2255 •••	4953 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0, R_{targ}]$
R : $R \in (R_{targ}, R_{max}]$
R : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h264 main abr
GOP Mode: 30 f
Compression: 30
ZS Strength: 50

Figure B.11: Stream quality analysis for Axis Q8752-E Zipstream Strength 50 test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	10 •	13 ••	15 ••	23 •	32 •	46 ••••	47 ••••	49 ••••	49 ••••	47 ••••	46 ••••	44 ••••	46 ••••
320x180 @ 2 FPS	12 •	16 •	24 ••	26 •	33 •••	51 •••	69 ••••	68 ••••	72 ••••	71 ••••	70 ••••	70 ••••	72 ••••
320x180 @ 5 FPS	10 •	12 •	21 •	22 •	25 •••	49 •••	73 ••••	73 ••••	69 ••••	62 ••••	71 ••••	80 ••••	71 ••••
320x180 @ 15 FPS	13 •	15 •	17 •	17 •••	26 ••	55 ••••	109 ••••	142 ••••	141 ••••	138 ••••	154 ••••	133 ••••	143 ••••
320x180 @ 30 FPS	19 •	21 •	27 •	28 •	31 •	70 •••	112 •••	222 •••	243 ••••	258 ••••	217 ••••	216 ••••	249 ••••
480x270 @ 1 FPS	18 •	19 •	25 ••	28 •	38 ••	66 ••	94 •••	121 ••••	117 ••••	114 ••••	123 ••••	121 ••••	129 ••••
480x270 @ 2 FPS	18 •	20 •	30 •	34 •	42 ••	66 •••	119 •••	155 ••••	162 ••••	163 ••••	161 ••••	160 ••••	162 ••••
480x270 @ 5 FPS	17 •	17 •	26 •	26 •	32 ••	52 •••	106 •••	150 ••••	151 ••••	141 ••••	145 ••••	146 ••••	149 ••••
480x270 @ 15 FPS	20 •	23 •	28 •	29 •	44 ••	60 •••	95 •••	243 •••	254 ••••	267 ••••	283 ••••	250 ••••	272 ••••
480x270 @ 30 FPS	30 •	34 •	37 •	41 •	54 •	63 •••	114 •••	275 •••	378 •••	466 •••	443 ••••	473 ••••	461 ••••
800x450 @ 1 FPS	33 •	33 •	43 •	45 •	56 •	100 •••	143 •••	202 ••	386 •••	357 ••••	386 ••••	395 ••••	383 ••••
800x450 @ 2 FPS	43 •	44 •	54 •	56 •	73 •	118 •••	168 ••••	330 •••	428 •••	460 •••	551 ••••	521 ••••	540 ••••
800x450 @ 5 FPS	52 •	50 •	53 •	60 •	64 •	95 ••	145 ••••	248 •••	368 •••	437 •••	509 ••••	534 ••••	546 ••••
800x450 @ 15 FPS	78 •	77 •	68 •	69 •	86 •	109 ••	121 •••	255 •••	403 ••••	555 •••	953 •••	1051 ••••	1006 ••••
800x450 @ 30 FPS	101 •	98 •	108 •	97 •	106 •	143 •	168 •••	320 •••	497 •••	654 •••	1313 •••	1664 ••••	1644 ••••
1280x720 @ 1 FPS	85 •	89 •	87 •	89 •	86 •	143 ••	190 •••	309 ••••	322 •	469 •••	962 •••	1006 ••••	960 ••••
1280x720 @ 2 FPS	119 •	117 •	114 •	118 •	136 •	182 •	271 ••	342 •••	526 •••	650 •	1182 •	1517 ••••	1464 ••••
1280x720 @ 5 FPS	150 •	152 •	152 •	152 •	141 •	167 •	226 ••	345 •••	517 •••	615 •••	1025 •••	1643 •••	1720 ••••
1280x720 @ 15 FPS	234 •	238 •	232 •	240 •	228 •	241 ••	262 ••	344 •••	427 •••	526 •••	989 •••	2375 •••	3144 ••••
1280x720 @ 30 FPS	293 •	295 •	291 •	287 •	285 •	296 •	358 •	425 •••	503 •••	679 •••	1288 •••	1837 ••••	4287 •••
1920x1080 @ 1 FPS	212 •	209 •	212 •	210 •	213 •	210 •	249 •	366 •••	451 •••	513 •••	1110 •	2228 •••	2238 ••••
1920x1080 @ 2 FPS	244 •	249 •	242 •	243 •	236 •	241 •	329 •	479 ••	660 ••	719 ••••	1262 ••••	2051 •	3367 ••••
1920x1080 @ 5 FPS	366 •	332 •	340 •	352 •	358 •	333 •	368 •	490 •••	617 ••	697 •••	1309 ••••	2496 •••	4936 •••
1920x1080 @ 15 FPS	593 •	593 •	592 •	534 •	565 •	625 •	548 •	668 ••	703 •	872 ••	1116 •••	1876 ••••	3860 ••••
1920x1080 @ 30 FPS	773 •	838 •	840 •	829 •	796 •	838 •	827 •	835 •	914 •	983 •	1344 •••	2037 •••	4130 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R (green) : $R \in [0, R_{targ}]$
R (yellow) : $R \in (R_{targ}, R_{max}]$
R (red) : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Axis Q8752-E
Scene: scene1
Encoding: h264 main abr
GOP Mode: 1 f - 300 f
Compression: 30
ZS Strength: 30

Figure B.12: Stream quality analysis for Axis Q8752-E Zipstream Strength 30 with Dynamic GOP Interval test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x180 @ 1 FPS	7 •	9 •	19 ••	21 •••	29 •	52 ••••	52 ••••	51 ••••	52 ••••	52 ••••	52 ••••	49 ••••	53 ••••
320x180 @ 2 FPS	9 •	13 •	19 ••	23 ••	38 ••	86 •••	93 ••••	94 ••••	89 ••••	86 ••••	91 ••••	86 ••••	86 ••••
320x180 @ 5 FPS	14 •	15 •	23 ••	24 ••	41 •••	82 •••	166 •••	163 ••••	170 ••••	179 ••••	163 ••••	175 ••••	172 ••••
320x180 @ 15 FPS	20 •	24 •	38 •	42 •	48 ••	81 •••	160 •••	312 •••	420 ••••	378 ••••	409 ••••	400 ••••	446 ••••
320x180 @ 30 FPS	35 •	38 •	49 •	54 •	77 •	90 •••	161 •••	292 •••	471 •••	569 •••	627 ••••	688 ••••	681 ••••
480x270 @ 1 FPS	9 •	10 •	19 •	21 •	32 ••	86 •	87 ••••	91 ••••	94 ••••	97 ••••	98 ••••	91 ••••	94 ••••
480x270 @ 2 FPS	10 •	16 •	25 •	24 •	39 •••	84 •••	157 •••	161 ••••	164 ••••	156 ••••	152 ••••	156 ••••	172 ••••
480x270 @ 5 FPS	20 •	23 •	29 •	31 •	40 ••	88 •••	190 •••	263 •••	267 ••••	227 ••••	275 ••••	279 ••••	268 ••••
480x270 @ 15 FPS	39 •	36 •	46 •	47 •	71 •	92 •••	165 •••	309 •••	514 •••	587 •••	732 ••••	619 ••••	685 ••••
480x270 @ 30 FPS	63 •	62 •	65 •	67 •	86 •	147 •	159 •••	307 •••	462 •••	598 •••	1006 •••	1008 ••••	1086 ••••
800x450 @ 1 FPS	21 •	21 •	20 •	20 •	29 •••	92 •••	133 ••	260 •••	276 ••••	235 ••••	267 ••••	311 ••••	269 ••••
800x450 @ 2 FPS	26 •	26 •	32 •	32 •	47 •	87 •••	180 •••	370 •••	492 •••	450 ••••	501 ••••	434 ••••	508 ••••
800x450 @ 5 FPS	58 •	57 •	58 •	56 •	62 •	103 ••	184 •••	376 •••	441 •••	718 •••	796 ••••	897 ••••	813 ••••
800x450 @ 15 FPS	109 •	109 •	106 •	111 •	98 •	155 ••	219 ••	310 •••	509 •••	632 •••	1313 •••	2046 ••••	1928 ••••
800x450 @ 30 FPS	166 •	164 •	166 •	160 •	166 •	187 •	311 •	362 •••	438 •••	599 •••	1183 •••	2481 •••	3288 ••••
1280x720 @ 1 FPS	53 •	51 •	53 •	50 •	44 •	68 ••	163 •••	351 •••	405 •	546 •••	652 ••••	711 ••••	686 ••••
1280x720 @ 2 FPS	64 •	64 •	66 •	65 •	69 •	118 •	166 ••	360 •••	535 •••	714 •••	1277 •••	1248 ••••	1285 ••••
1280x720 @ 5 FPS	155 •	153 •	150 •	154 •	151 •	166 •	221 •••	368 •••	571 •••	736 •••	1144 •••	2528 •••	2283 ••••
1280x720 @ 15 FPS	298 •	290 •	306 •	308 •	301 •	300 •	351 •	512 ••	562 •••	666 •••	1353 •••	2689 •••	4956 •••
1280x720 @ 30 FPS	429 •	425 •	431 •	424 •	421 •	430 •	451 •	655 •	870 •	834 ••	1191 •••	2499 •••	4163 •••
1920x1080 @ 1 FPS	123 •	122 •	124 •	123 •	125 •	124 •	169 ••	364 •••	438 •••	583 •••	1329 •	1938 ••••	1745 ••••
1920x1080 @ 2 FPS	147 •	143 •	155 •	146 •	151 •	157 •	241 •	337 ••	548 •••	557 •••	1378 •••	2719 •	3642 ••••
1920x1080 @ 5 FPS	360 •	355 •	356 •	345 •	353 •	331 •	357 •	501 •	579 •••	726 •••	1477 •••	2939 •••	5394 •••
1920x1080 @ 15 FPS	736 •	731 •	732 •	767 •	767 •	770 •	759 •	750 •	897 •	1068 •	1475 •••	2839 •••	5982 •••
1920x1080 @ 30 FPS	1085 •	1068 •	1070 •	1063 •	1074 •	1078 •	1096 •	1058 •	1154 •	1259 •	2067 ••	2499 •••	5259 •••

R	:	measured average bitrate (kbps)
R_{nom}	:	nominal bitrate for link class (kbps)
R_{100}	:	net-limit test rate (100% of R_{nom})
R_{80}	:	net-limit test rate (80% of R_{nom})
R_{50}	:	net-limit test rate (50% of R_{nom})
R_{max}	:	specified max. rate (80% of R_{nom})
R_{targ}	:	specified target rate (80% of R_{max})
F_r	:	# frames received
F_e	:	# frames expected

R (green)	:	$R \in [0, R_{targ}]$
R (yellow)	:	$R \in (R_{targ}, R_{max}]$
R (red)	:	$R \in (R_{max}, \infty)$
••••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	:	$F_r \div F_e \geq 90\%$ for R_{100}
•	:	$F_r \div F_e \geq 90\%$ for no test rates

Device:	Axis Q8752-E
Scene:	scene1
Encoding:	h264 main abr
GOP Mode:	30 f
Compression:	30
ZS Strength:	off

Figure B.13: Stream quality analysis for Axis Q8752-E TCP Streaming test

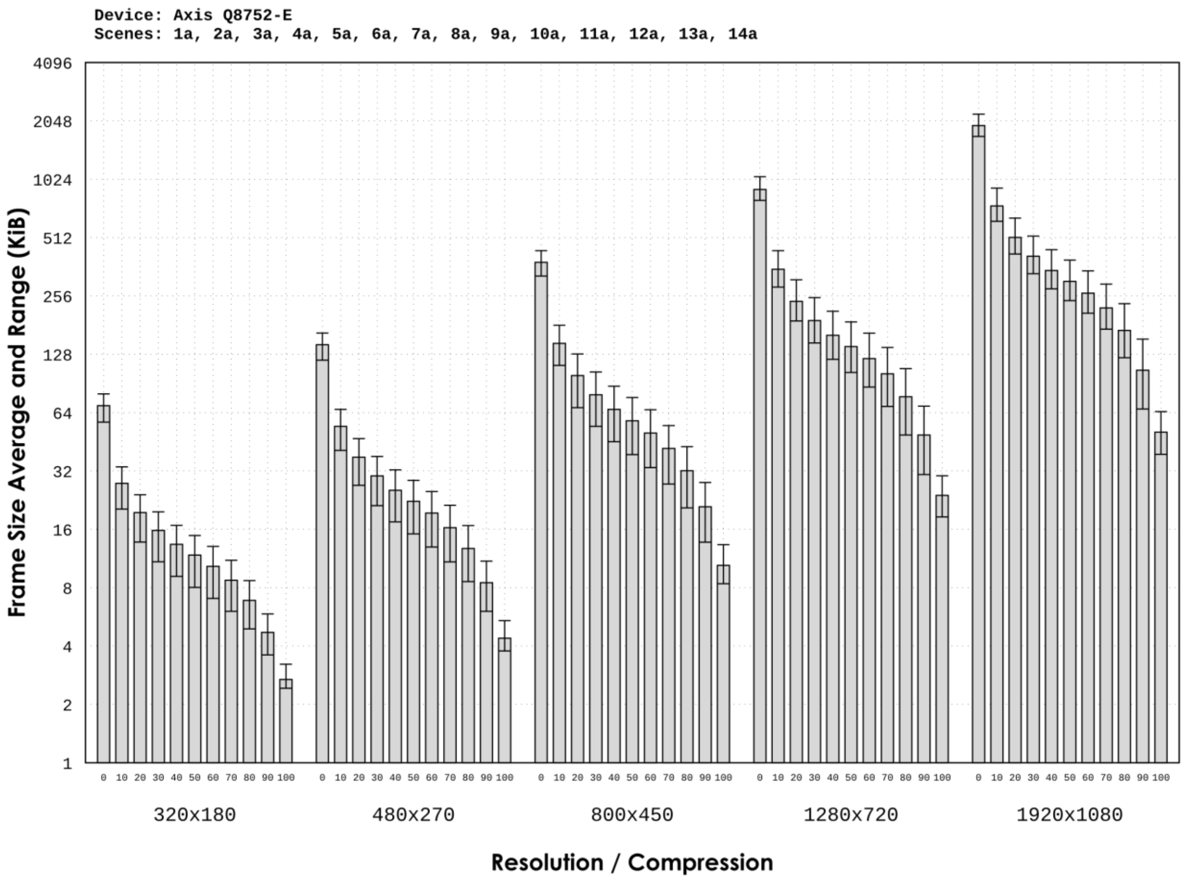

Figure B.14: Image sizes for Axis Q8752-E JPEG test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
512x288 @ 1 FPS	5 •	17 •	29 •	31 ••	54 •	123 •••	275 •	654 •	717 •	789 ••	823 ••••	826 ••••	830 ••••
512x288 @ 2 FPS	11 •	15 •	30 •	34 ••	48 ••	107 ••	204 ••	434 ••	659 ••	857 ••	1783 ••	1723 ••••	1807 ••••
512x288 @ 5 FPS	22 •	22 •	33 •	36 •	53 ••	111 ••	221 •••	436 •••	642 •••	847 •••	1677 •••	3311 •••	4180 ••••
512x288 @ 15 FPS	57 •	58 •	58 •	57 •	71 •	130 ••	231 ••	442 ••	649 •••	844 •••	1675 •••	3300 •••	6608 •••
512x288 @ 30 FPS	105 •	102 •	101 •	106 •	106 •	156 •	257 ••	466 ••	679 ••	866 ••	1684 •••	3339 •••	6605 •••
768x432 @ 1 FPS	11 •	10 •	29 •	31 •	46 ••	104 •	239 ••	618 •	1048 •	1231 •	1685 ••	1766 ••••	1782 ••••
768x432 @ 2 FPS	21 •	21 •	26 •	31 •	51 ••	117 ••	206 ••	702 ••	623 ••	834 ••	1655 ••	3791 ••	3861 ••••
768x432 @ 5 FPS	44 •	45 •	43 •	45 •	57 •	108 ••	208 •••	436 •••	638 •••	817 •••	1666 •••	3350 •••	6588 ••
768x432 @ 15 FPS	118 •	116 •	147 •	113 •	115 •	135 ••	230 ••	432 ••	652 ••	843 •••	1648 •••	3311 •••	6636 •••
768x432 @ 30 FPS	210 •	202 •	210 •	287 •	204 •	209 •	262 ••	478 ••	667 ••	863 ••	1679 •••	3373 •••	6628 •••
1280x720 @ 1 FPS	22 •	22 •	26 •	22 •	25 •	120 ••	157 •	510 •••	887 •	1301 •	2439 •	3524 •	4284 •••
1280x720 @ 2 FPS	48 •	47 •	60 •	47 •	51 •	115 ••	226 ••	431 ••	650 ••	809 ••	1603 ••	3467 ••	6967 ••
1280x720 @ 5 FPS	99 •	95 •	97 •	96 •	97 •	123 ••	209 ••	408 •••	617 •••	807 •••	1682 •••	3356 •••	6571 •••
1280x720 @ 15 FPS	241 •	247 •	234 •	249 •	249 •	246 •	265 ••	456 ••	642 ••	830 •••	1665 •••	3281 •••	6655 •••
1280x720 @ 30 FPS	417 •	441 •	440 •	446 •	441 •	447 •	443 •	493 ••	711 ••	891 ••	1714 •••	3296 •••	6646 •••
1920x1080 @ 1 FPS	48 •	57 •	46 •	49 •	52 •	114 ••	234 ••	401 ••	557 ••	897 •	2244 •	4941 •	6733 •
1920x1080 @ 2 FPS	98 •	101 •	102 •	99 •	133 •	106 ••	232 ••	435 •••	581 ••	825 ••	1517 ••	3059 ••	7340 •
1920x1080 @ 5 FPS	201 •	205 •	196 •	202 •	203 •	205 •	241 ••	438 ••	606 •••	839 •••	1619 •••	3230 •••	6569 ••
1920x1080 @ 15 FPS	492 •	509 •	515 •	518 •	522 •	490 •	506 •	474 ••	663 •••	843 •••	1615 •••	3298 •••	6531 •••
1920x1080 @ 30 FPS	912 •	853 •	917 •	900 •	867 •	1105 •	929 •	902 •	826 •	967 ••	1643 •••	3391 •••	6706 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0, R_{targ}]$
R : $R \in (R_{targ}, R_{max}]$
R : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq$ 90% for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq$ 90% for R_{100}, R_{80}
•• : $F_r \div F_e \geq$ 90% for R_{100}
• : $F_r \div F_e \geq$ 90% for no test rates

Device: Bosch 7100i
Scene: scene1
Encoding: H.264
Frame Mode: IBP
GOP Mode: 30 f

Figure B.15: Stream quality analysis for Bosch MIC inteox 7100i Baseline (H.264 High) test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
512x288 @ 1 FPS	6 •	13 •	36 •	30 •	5 •	139 ••	264 ••	531 •	680 ••	815 ••	855 ••••	852 ••••	817 ••••
512x288 @ 2 FPS	8 •	16 •	34 •	36 •	54 ••	109 ••	212 ••	597 ••	666 ••	856 ••	1649 •••	1630 ••••	1647 ••••
512x288 @ 5 FPS	16 •	18 •	33 •	37 •	54 ••	112 ••	221 ••	437 •••	644 •••	834 •••	1670 •••	3331 •••	4009 ••••
512x288 @ 15 FPS	41 •	41 •	47 •	52 •	69 •	131 ••	239 ••	448 ••	649 •••	840 •••	1671 •••	3313 •••	6657 •••
512x288 @ 30 FPS	74 •	76 •	76 •	76 •	95 •	152 •	263 ••	471 ••	676 ••	874 ••	1692 •••	3335 •••	6658 •••
768x432 @ 1 FPS	7 •	7 •	31 •	32 ••	61 ••	126 ••	244 •	527 ••	710 ••	875 ••	1627 •••	1827 ••••	1811 ••••
768x432 @ 2 FPS	13 •	13 •	30 ••	35 ••	51 ••	121 ••	224 ••	414 ••	665 ••	906 ••	1682 ••	3442 •••	3515 ••••
768x432 @ 5 FPS	26 •	27 •	32 •	36 •	58 ••	115 ••	217 •••	431 •••	648 •••	847 •••	1676 •••	3325 •••	6632 •••
768x432 @ 15 FPS	65 •	62 •	66 •	67 •	73 •	133 ••	237 ••	436 ••	656 ••	858 •••	1667 •••	3349 •••	6618 •••
768x432 @ 30 FPS	114 •	116 •	118 •	114 •	118 •	162 •	268 ••	466 ••	690 ••	861 ••	1694 •••	3341 •••	6615 •••
1280x720 @ 1 FPS	14 •	13 •	13 ••	16 •	49 ••	108 •••	196 •	539 ••	719 ••	868 ••	1711 ••	3312 •••	4322 ••••
1280x720 @ 2 FPS	25 •	32 •	26 •	26 •	51 ••	131 ••	246 ••	430 •••	659 ••	906 ••	1763 ••	3678 ••	6698 •••
1280x720 @ 5 FPS	48 •	51 •	52 •	49 •	51 •	121 ••	223 •••	440 ••	647 •••	850 •••	1670 •••	3281 •••	6694 •••
1280x720 @ 15 FPS	118 •	110 •	122 •	118 •	120 •	140 •	242 ••	458 ••	646 •••	831 •••	1689 •••	3338 •••	6676 •••
1280x720 @ 30 FPS	204 •	193 •	230 •	207 •	209 •	211 •	286 •	462 ••	684 ••	924 ••	1755 •••	3373 •••	6686 •••
1920x1080 @ 1 FPS	28 •	26 •	28 •	27 •	26 ••	89 ••	210 •••	493 ••	711 ••	876 ••	1744 ••	3466 ••	6621 •••
1920x1080 @ 2 FPS	50 •	53 •	51 •	54 •	50 •	124 ••	250 •••	466 •••	646 •••	861 ••	1724 ••	3591 •••	7246 ••
1920x1080 @ 5 FPS	103 •	99 •	102 •	101 •	102 •	113 ••	231 ••	424 •••	637 •••	816 •••	1649 •••	3369 •••	6575 •••
1920x1080 @ 15 FPS	210 •	237 •	238 •	235 •	229 •	237 •	248 ••	450 ••	659 ••	857 •••	1702 •••	3342 •••	6637 •••
1920x1080 @ 30 FPS	378 •	399 •	467 •	364 •	389 •	394 •	399 •	502 ••	711 ••	922 ••	1682 •••	3368 •••	6727 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R	: $R \in [0, R_{targ}]$
R	: $R \in (R_{targ}, R_{max}]$
R	: $R \in (R_{max}, \infty)$
••••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	: $F_r \div F_e \geq 90\%$ for R_{100}
•	: $F_r \div F_e \geq 90\%$ for no test rates

Device: Bosch 7100i
Scene: scene1
Encoding: H.265
Frame Mode: IBP
GOP Mode: 30 f

Figure B.16: Stream quality analysis for Bosch MIC inteox 7100i H.265 Main Profile test

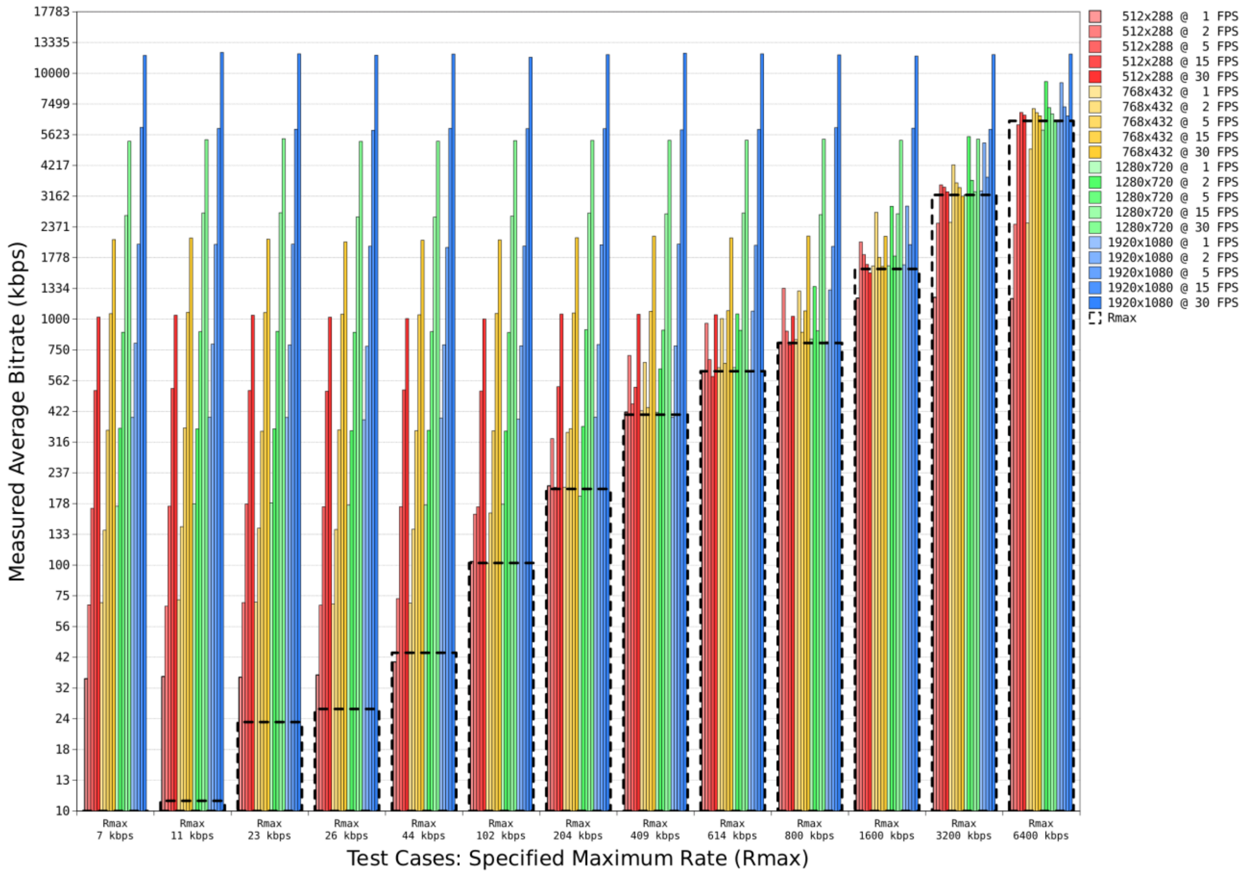

Figure B.17: Average bitrates for Bosch MIC inteox 7100i M-JPEG test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
512x288 @ 1 FPS	8 •	15 •	23 ••	29 •	31 •	147 •••	189 •	597 •	721 •	797 ••	850 ••••	849 ••••	848 ••••
512x288 @ 2 FPS	12 •	16 •	26 •	29 ••	44 ••	101 ••	204 ••	411 ••	600 ••	804 ••	1798 ••	1809 ••••	1799 ••••
512x288 @ 5 FPS	23 •	24 •	40 •	36 •	53 ••	110 ••	217 ••	428 ••	641 •••	835 •••	1656 •••	3314 •••	4084 ••••
512x288 @ 15 FPS	57 •	53 •	55 •	57 •	70 •	132 ••	230 ••	446 ••	659 •••	847 •••	1666 •••	3317 •••	6622 •••
512x288 @ 30 FPS	94 •	97 •	98 •	95 •	104 •	156 •	259 ••	464 ••	679 ••	874 ••	1688 •••	3339 •••	6656 •••
768x432 @ 1 FPS	13 •	14 •	28 •	29 •	42 •	64 ••	218 ••	668 •	1074 •	1227 •	1695 ••	1788 ••••	1879 ••••
768x432 @ 2 FPS	23 •	24 •	28 •	31 •	46 •	109 ••	187 ••	413 ••	593 ••	753 ••	1689 ••	3602 ••	3766 ••••
768x432 @ 5 FPS	47 •	47 •	46 •	47 •	57 •	110 ••	216 ••	429 •••	642 •••	832 •••	1666 •••	3305 •••	6596 ••
768x432 @ 15 FPS	112 •	113 •	114 •	109 •	110 •	136 ••	237 ••	447 ••	653 •••	853 •••	1679 •••	3333 •••	6561 •••
768x432 @ 30 FPS	199 •	189 •	198 •	199 •	198 •	198 •	260 ••	475 ••	682 ••	868 ••	1703 •••	3340 •••	6669 •••
1280x720 @ 1 FPS	28 •	32 •	29 •	48 •	50 •	36 •	140 ••	671 •	792 •	1188 ••	2493 •	3397 •	4331 •••
1280x720 @ 2 FPS	52 •	50 •	50 •	54 •	53 •	111 ••	199 ••	377 ••	607 ••	755 ••	1568 ••	3304 •	6983 •
1280x720 @ 5 FPS	100 •	101 •	97 •	98 •	100 •	125 ••	215 ••	420 ••	625 ••	825 •••	1664 •••	3305 •••	6596 ••
1280x720 @ 15 FPS	237 •	236 •	236 •	236 •	238 •	228 •	261 ••	445 ••	637 •••	845 •••	1652 •••	3298 •••	6631 •••
1280x720 @ 30 FPS	398 •	396 •	474 •	523 •	397 •	402 •	408 •	496 ••	691 ••	881 ••	1676 •••	3361 •••	6665 •••
1920x1080 @ 1 FPS	60 •	67 •	68 •	72 •	61 •	61 ••	191 •	273 ••	510 ••	791 •	2150 •	4537 •	6627 •
1920x1080 @ 2 FPS	111 •	101 •	108 •	113 •	112 •	111 •	204 ••	385 ••	618 ••	770 ••	1547 •	3132 ••	6975 •
1920x1080 @ 5 FPS	198 •	212 •	207 •	201 •	208 •	200 •	240 ••	429 ••	631 •••	797 •••	1642 •••	3310 •••	6575 ••
1920x1080 @ 15 FPS	487 •	481 •	472 •	516 •	487 •	487 •	490 •	514 ••	676 •••	857 •••	1602 •••	3331 •••	6568 •••
1920x1080 @ 30 FPS	809 •	832 •	770 •	793 •	808 •	818 •	812 •	780 •	799 •	947 ••	1712 •••	3399 •••	6522 ••

- R : measured average bitrate (kbps)
- R_{nom} : nominal bitrate for link class (kbps)
- R_{100} : net-limit test rate (100% of R_{nom})
- R_{80} : net-limit test rate (80% of R_{nom})
- R_{50} : net-limit test rate (50% of R_{nom})
- R_{max} : specified max. rate (80% of R_{nom})
- R_{targ} : specified target rate (80% of R_{max})
- F_r : # frames received
- F_e : # frames expected

- R : $R \in [0, R_{targ}]$
- R : $R \in (R_{targ}, R_{max}]$
- R : $R \in (R_{max}, \infty)$
- •••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
- ••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
- •• : $F_r \div F_e \geq 90\%$ for R_{100}
- • : $F_r \div F_e \geq 90\%$ for no test rates

Device: Bosch 7100i
Scene: scene1
Encoding: H.264
Frame Mode: IBP
GOP Mode: 5 s

Figure B.18: Stream quality analysis for Bosch MIC inteox 7100i Varying GOP Interval with Frame Rate test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
512x288 @ 1 FPS	10 •	13 •	26 ••	21 ••	35 •	70 ••	316 •	616 •	717 ••	796 ••	832 ••••	838 ••••	827 ••••
512x288 @ 2 FPS	11 •	14 •	28 •	29 ••	50 ••	108 ••	356 ••	424 ••	642 ••	842 ••	1740 •••	1677 ••••	1736 ••••
512x288 @ 5 FPS	22 •	22 •	32 •	35 •	53 ••	110 ••	215 ••	423 •••	641 •••	832 •••	1668 •••	3285 •••	4023 ••••
512x288 @ 15 FPS	55 •	54 •	54 •	55 •	71 •	129 ••	226 ••	448 ••	655 •••	845 •••	1666 •••	3311 •••	6606 •••
512x288 @ 30 FPS	98 •	95 •	99 •	100 •	101 •	157 •	261 ••	456 ••	670 ••	868 ••	1686 •••	3329 •••	6644 •••
768x432 @ 1 FPS	11 •	10 •	27 •	32 •	44 ••	95 •	238 ••	633 •	1047 •	1247 •	1652 ••	1763 ••••	1758 ••••
768x432 @ 2 FPS	21 •	20 •	26 •	31 •	52 ••	110 ••	212 ••	755 ••	606 ••	803 ••	1681 ••	3679 ••	3723 ••••
768x432 @ 5 FPS	42 •	42 •	42 •	41 •	55 ••	110 ••	213 ••	430 ••	631 •••	828 •••	1636 •••	3270 •••	6646 ••
768x432 @ 15 FPS	106 •	106 •	109 •	108 •	104 •	135 ••	234 ••	438 ••	655 •••	851 •••	1665 •••	3322 •••	6590 •••
768x432 @ 30 FPS	195 •	193 •	191 •	195 •	193 •	183 •	258 ••	480 ••	657 ••	890 ••	1695 •••	3337 •••	6596 •••
1280x720 @ 1 FPS	24 •	22 •	23 •	22 •	50 •	129 •	161 ••	491 ••	917 •	1214 ••	2415 •	3499 ••	4278 •••
1280x720 @ 2 FPS	45 •	43 •	44 •	48 •	44 •	109 ••	210 ••	416 ••	625 ••	830 ••	1585 ••	3315 ••	6963 ••
1280x720 @ 5 FPS	88 •	90 •	90 •	87 •	91 •	116 ••	217 ••	427 •••	635 •••	836 •••	1634 •••	3256 •••	6493 ••
1280x720 @ 15 FPS	225 •	228 •	225 •	231 •	269 •	232 •	263 ••	450 ••	675 •••	852 •••	1659 •••	3298 •••	6609 •••
1280x720 @ 30 FPS	392 •	395 •	404 •	403 •	392 •	468 •	411 •	496 ••	681 ••	862 ••	1721 •••	3294 •••	6637 ••
1920x1080 @ 1 FPS	48 •	47 •	44 •	53 •	47 •	122 •	71 •	339 •	667 •••	970 ••	2300 •	4829 •	6700 •
1920x1080 @ 2 FPS	96 •	92 •	92 •	87 •	94 •	112 ••	210 ••	410 ••	651 ••	830 •••	1659 ••	3228 ••	7061 •
1920x1080 @ 5 FPS	186 •	181 •	188 •	199 •	176 •	185 •	231 ••	429 ••	616 •••	847 •••	1642 •••	3279 •••	6448 ••
1920x1080 @ 15 FPS	444 •	462 •	439 •	471 •	558 •	468 •	465 •	504 ••	652 •••	860 •••	1689 •••	3352 •••	6626 •••
1920x1080 @ 30 FPS	771 •	809 •	796 •	811 •	795 •	782 •	1168 •	809 •	801 ••	917 ••	1731 •••	3387 •••	6668 •••

- R : measured average bitrate (kbps)
- R_{nom} : nominal bitrate for link class (kbps)
- R_{100} : net-limit test rate (100% of R_{nom})
- R_{80} : net-limit test rate (80% of R_{nom})
- R_{50} : net-limit test rate (50% of R_{nom})
- R_{max} : specified max. rate (80% of R_{nom})
- R_{targ} : specified target rate (80% of R_{max})
- F_r : # frames received
- F_e : # frames expected

- R (green) : $R \in [0, R_{targ}]$
- R (yellow) : $R \in (R_{targ}, R_{max}]$
- R (red) : $R \in (R_{max}, \infty)$
- •••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
- ••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
- •• : $F_r \div F_e \geq 90\%$ for R_{100}
- • : $F_r \div F_e \geq 90\%$ for no test rates

Device: Bosch 7100i
Scene: scene1
Encoding: H.264
Frame Mode: IBP
GOP Mode: auto f - auto f

Figure B.19: Stream quality analysis for Bosch MIC inteox 7100i Dynamic GOP Interval test

	R_{nom}, R_{max}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	7	11	23	26	44	102	204	409	614	800	1600	3200	6400
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
512x288 @ 1 FPS	7 •	15 •	6 •	31 ••	54 •	117 •••	310 ••	650 •	802 •	869 ••	920 ••••	910 ••••	884 ••••
512x288 @ 2 FPS	12 •	17 •	32 •	35 •	52 ••	110 ••	223 ••	429 ••	645 ••	852 ••	1777 ••	1805 ••••	1795 ••••
512x288 @ 5 FPS	26 •	26 •	37 •	39 •	56 •	115 ••	227 ••	448 ••	664 ••	862 •••	1715 •••	3395 •••	4236 ••••
512x288 @ 15 FPS	64 •	65 •	63 •	66 •	77 •	134 ••	244 ••	466 ••	670 ••	866 ••	1706 •••	3385 •••	6812 •••
512x288 @ 30 FPS	118 •	119 •	119 •	118 •	119 •	170 •	278 ••	487 ••	710 ••	898 ••	1739 ••	3406 •••	6774 •••
768x432 @ 1 FPS	12 •	12 •	32 •	34 •	49 •	127 •	219 •••	615 •	1081 •	1270 •	1855 ••	1953 ••••	1957 ••••
768x432 @ 2 FPS	23 •	22 •	29 •	31 •	56 •	117 ••	228 ••	450 ••	652 ••	825 ••	1706 ••	3768 ••	3844 ••••
768x432 @ 5 FPS	49 •	48 •	47 •	49 •	61 •	120 ••	223 ••	447 ••	662 ••	858 ••	1713 •••	3385 •••	6760 •••
768x432 @ 15 FPS	119 •	125 •	124 •	120 •	119 •	141 •	248 ••	458 ••	676 ••	873 ••	1713 •••	3386 •••	6726 •••
768x432 @ 30 FPS	221 •	225 •	229 •	226 •	222 •	220 •	278 ••	489 ••	701 ••	929 ••	1727 ••	3439 •••	6799 •••
1280x720 @ 1 FPS	26 •	24 •	26 •	27 •	59 •	103 •	264 •	416 •••	856 ••	1300 •	2466 •	3722 ••	4685 •••
1280x720 @ 2 FPS	47 •	47 •	49 •	47 •	50 •	125 ••	239 ••	448 ••	659 ••	837 ••	1592 ••	3291 ••	7055 ••
1280x720 @ 5 FPS	105 •	103 •	100 •	101 •	105 •	119 ••	234 ••	444 ••	672 ••	860 ••	1729 ••	3428 •••	6794 •••
1280x720 @ 15 FPS	258 •	261 •	251 •	259 •	254 •	244 •	259 ••	455 ••	685 ••	843 •••	1692 •••	3413 •••	6742 ••
1280x720 @ 30 FPS	435 •	464 •	462 •	444 •	466 •	455 •	457 •	516 ••	702 ••	902 ••	1765 ••	3393 •••	6828 •••
1920x1080 @ 1 FPS	52 •	53 •	54 •	55 •	51 •	114 •	271 ••	541 •	519 •••	881 •••	2294 ••	4990 •	7171 ••
1920x1080 @ 2 FPS	101 •	101 •	98 •	105 •	101 •	102 •	236 ••	438 ••	657 ••	844 ••	1671 ••	3047 ••	6675 ••
1920x1080 @ 5 FPS	214 •	211 •	216 •	214 •	214 •	215 •	232 ••	445 ••	683 ••	838 ••	1700 •••	3387 •••	6773 •••
1920x1080 @ 15 FPS	535 •	515 •	532 •	533 •	503 •	529 •	528 •	512 ••	691 ••	857 ••	1668 ••	3421 •••	6790 •••
1920x1080 @ 30 FPS	944 •	942 •	939 •	887 •	927 •	914 •	864 •	916 •	923 •	993 ••	1704 ••	3372 ••	6844 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0, R_{targ}]$
R : $R \in (R_{targ}, R_{max}]$
R : $R \in (R_{max}, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: Bosch 7100i
Scene: scene1
Encoding: H.264
Frame Mode: IBP
GOP Mode: 30 f

Figure B.20: Stream quality analysis for Bosch MIC inteox 7100i TCP Streaming test

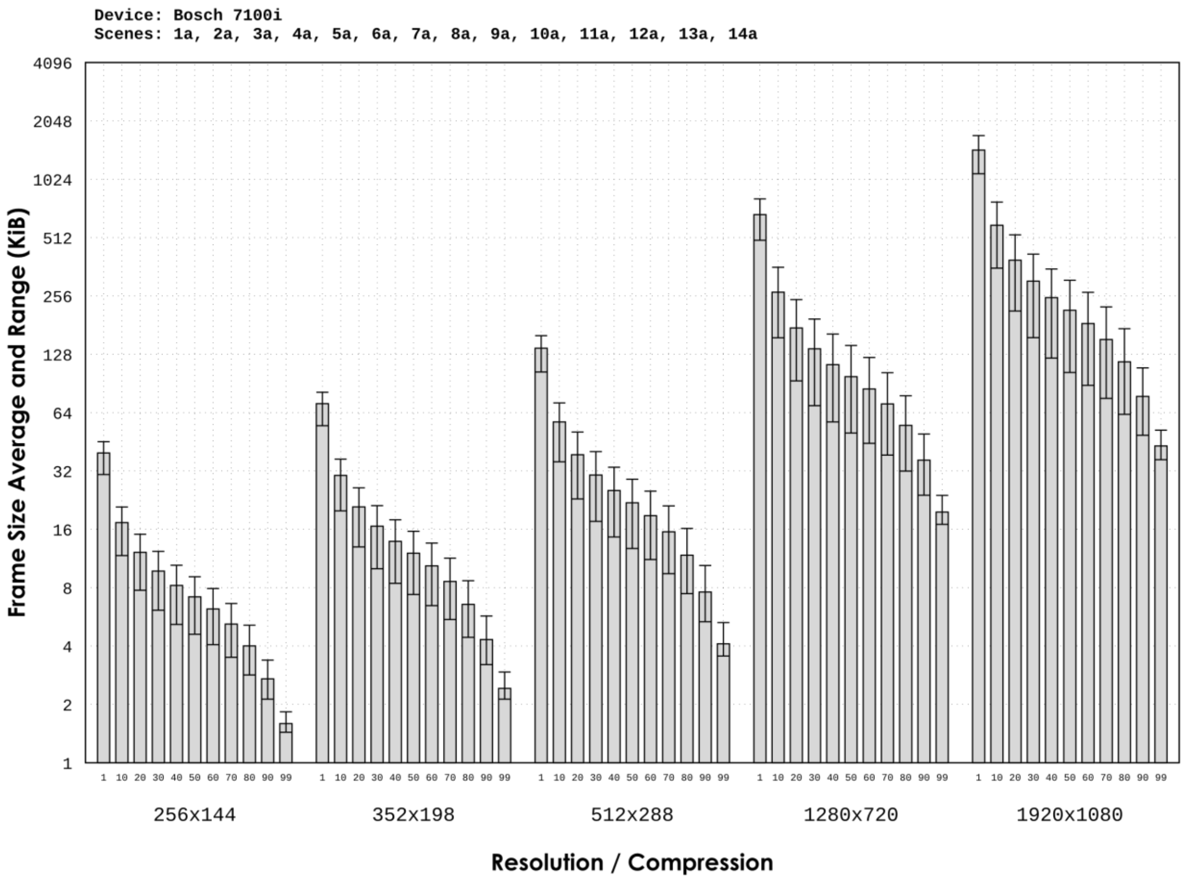

Figure B.21: Image sizes for Bosch MIC inteox 7100i JPEG test

	R_{nom}, R_{targ} (kbps)					
	512	768	1000	2000	4000	8000
	327	491	640	1280	2560	5120
352x240 @ 1 FPS	243 •••	241 ••••	238 ••••	254 ••••	256 ••••	240 ••••
352x240 @ 2 FPS	340 •••	447 •••	426 ••••	414 ••••	422 ••••	431 ••••
352x240 @ 5 FPS	340 •••	512 •••	673 •••	886 ••••	877 ••••	890 ••••
352x240 @ 15 FPS	344 •••	517 •••	673 •••	1344 •••	2223 •••	2220 ••••
352x240 @ 30 FPS	347 •••	523 •••	677 •••	1348 •••	2717 •••	4057 •••
720x480 @ 1 FPS	325 •••	495 •••	690 •••	1046 •••	1034 ••••	1086 ••••
720x480 @ 2 FPS	287 •••	437 •••	616 •••	1334 •••	1901 ••••	1824 ••••
720x480 @ 5 FPS	318 •••	465 •••	611 •••	1330 •••	2709 •••	4011 ••••
720x480 @ 15 FPS	355 •••	530 •••	688 •••	1365 •••	2719 •••	5384 •••
720x480 @ 30 FPS	354 •••	518 •••	674 •••	1363 •••	2691 •••	5433 •••
1280x720 @ 1 FPS	327 •••	491 •••	622 •••	1300 •••	2587 •••	2595 ••••
1280x720 @ 2 FPS	290 •••	442 •••	554 •••	1126 •••	2640 •••	4584 •••
1280x720 @ 5 FPS	332 •••	473 •••	598 •••	1152 •••	2600 •••	5367 •••
1280x720 @ 15 FPS	354 •••	529 •••	662 •••	1375 •••	2679 •••	5429 •••
1280x720 @ 30 FPS	350 •••	517 •••	675 •••	1344 •••	2719 •••	5420 •••
1920x1080 @ 1 FPS	324 •••	476 •••	594 •••	1265 •••	2595 •••	5383 •••
1920x1080 @ 2 FPS	288 •••	429 •••	562 •••	1139 •••	2268 •••	5420 •••
1920x1080 @ 5 FPS	328 •••	498 •••	620 •••	1174 •••	2240 •••	5204 •••
1920x1080 @ 15 FPS	381 •••	528 •••	663 •••	1330 •••	2731 •••	5366 •••
1920x1080 @ 30 FPS	529 •	586 •••	669 •••	1367 •••	2682 •••	5423 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R (green)	: $R \in [0, R_{targ}]$
R (yellow)	: $R \in (t, 1.25t]$
R (red)	: $R \in (1.25t, \infty)$
••••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	: $F_r \div F_e \geq 90\%$ for R_{100}
•	: $F_r \div F_e \geq 90\%$ for no test rates

Device: Cohu 4261
Scene: scene1
Encoding: H264 Main CBR
GOP Mode: 30 f
Constrained: Off

Figure B.22: Stream quality analysis for CostarHD RISE 4260HD Baseline (H.264 Main) test

	R_{nom}, R_{targ} (kbps)					
	512	768	1000	2000	4000	8000
	327	491	640	1280	2560	5120
352x240 @ 1 FPS	262 •••	258 ••••	258 ••••	267 ••••	252 ••••	232 ••••
352x240 @ 2 FPS	343 •••	424 •••	422 ••••	431 ••••	444 ••••	431 ••••
352x240 @ 5 FPS	342 •••	514 •••	673 •••	910 ••••	916 ••••	922 ••••
352x240 @ 15 FPS	353 •••	526 •••	686 •••	1364 •••	2299 •••	2215 ••••
352x240 @ 30 FPS	353 •••	522 •••	678 •••	1361 •••	2715 •••	4049 •••
720x480 @ 1 FPS	319 •••	526 •••	681 •••	991 •••	1094 ••••	1003 ••••
720x480 @ 2 FPS	303 •••	475 •••	607 •••	1313 •••	1824 ••••	1892 ••••
720x480 @ 5 FPS	318 •••	497 •••	612 •••	1325 •••	2686 •••	3962 ••••
720x480 @ 15 FPS	355 •••	530 •••	687 •••	1363 •••	2676 •••	5417 •••
720x480 @ 30 FPS	347 •••	527 •••	688 •••	1365 •••	2714 •••	5426 •••
1280x720 @ 1 FPS	338 •••	493 •••	637 •••	1327 •••	2438 •••	2700 ••••
1280x720 @ 2 FPS	301 •••	443 •••	575 •••	1157 •••	2630 •••	4729 •••
1280x720 @ 5 FPS	298 •••	468 •••	594 •••	1143 •••	2584 •••	5401 •••
1280x720 @ 15 FPS	355 •••	529 •••	689 •••	1336 •••	2727 •••	5426 •••
1280x720 @ 30 FPS	360 •••	519 •••	685 •••	1362 •••	2715 •••	5427 •••
1920x1080 @ 1 FPS	330 •••	495 •••	595 •••	1233 •••	2483 •••	5388 •••
1920x1080 @ 2 FPS	285 •••	440 •••	550 •••	1115 •••	2286 •••	5427 •••
1920x1080 @ 5 FPS	297 •••	479 •••	633 •••	1166 •••	2231 •••	5198 •••
1920x1080 @ 15 FPS	376 •••	529 •••	687 •••	1372 •••	2728 •••	5359 •••
1920x1080 @ 30 FPS	536 •	586 •••	696 •••	1339 •••	2716 •••	5420 •••

R	:	measured average bitrate (kbps)
R_{nom}	:	nominal bitrate for link class (kbps)
R_{100}	:	net-limit test rate (100% of R_{nom})
R_{80}	:	net-limit test rate (80% of R_{nom})
R_{50}	:	net-limit test rate (50% of R_{nom})
R_{max}	:	specified max. rate (80% of R_{nom})
R_{targ}	:	specified target rate (80% of R_{max})
F_r	:	# frames received
F_e	:	# frames expected

R (green)	:	$R \in [0, R_{targ}]$
R (yellow)	:	$R \in (t, 1.25t]$
R (red)	:	$R \in (1.25t, \infty)$
••••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	:	$F_r \div F_e \geq 90\%$ for R_{100}
•	:	$F_r \div F_e \geq 90\%$ for no test rates

Device:	Cohu 4261
Scene:	scene1
Encoding:	H264 High CBR
GOP Mode:	30 f
Constrained:	Off

Figure B.23: Stream quality analysis for CostarHD RISE 4260HD H.264 High Profile test

	R_{nom}, R_{targ} (kbps)					
	512	768	1000	2000	4000	8000
	327	491	640	1280	2560	5120
352x240 @ 1 FPS	292 •••	272 •	275 •	267 ••••	277 •	286 ••
352x240 @ 2 FPS	343 ••	455 •••	468 ••••	469 ••	480 •	465 •
352x240 @ 5 FPS	347 •••	516 •	680 •••	946 •	916 •	904 ••••
352x240 @ 15 FPS	345 ••	519 •	676 ••	1351 •	2261 ••	2271 •
352x240 @ 30 FPS	348 ••	522 •	678 •••	1350 •••	2700 •	3861 ••
720x480 @ 1 FPS	325 •••	468 •••	669 •	1160 •••	1061 ••••	1102 ••••
720x480 @ 2 FPS	307 •••	451 •••	594 •••	1324 •••	1966 ••••	1906 ••
720x480 @ 5 FPS	318 •••	485 •	620 •	1342 •••	2693 •••	4042 ••••
720x480 @ 15 FPS	343 •••	517 •••	674 •••	1346 •••	2702 •••	5397 •••
720x480 @ 30 FPS	347 •••	521 •••	676 •••	1350 •••	2698 ••	5410 •••
1280x720 @ 1 FPS	347 ••	495 ••	647 •••	1223 •••	2775 •••	2731 •••
1280x720 @ 2 FPS	316 •••	474 •••	607 •••	1178 •••	2682 •	4943 •••
1280x720 @ 5 FPS	322 •••	480 •••	614 •••	1189 •••	2700 •••	5355 •••
1280x720 @ 15 FPS	343 •••	513 •••	667 •••	1340 •••	2688 •••	5372 •
1280x720 @ 30 FPS	344 •••	519 •	674 •••	1346 •	2689 •••	5394 •••
1920x1080 @ 1 FPS	351 ••	514 •••	647 •••	1243 •••	2669 •••	5376 •
1920x1080 @ 2 FPS	319 •••	474 •••	611 •••	1198 •	2436 •••	5464 •••
1920x1080 @ 5 FPS	331 •••	504 •••	645 •••	1162 •••	2588 •••	5306 •••
1920x1080 @ 15 FPS	365 •	511 ••	665 •••	1341 ••	2668 •••	5525 ••
1920x1080 @ 30 FPS	446 ••	547 •••	682 •••	1360 •••	2711 •••	4955 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R	: $R \in [0, R_{targ}]$
R	: $R \in (t, 1.25t]$
R	: $R \in (1.25t, \infty)$
••••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	: $F_r \div F_e \geq 90\%$ for R_{100}
•	: $F_r \div F_e \geq 90\%$ for no test rates

Device: Cohu 4261
Scene: scene1
Encoding: H264 Main CBR
GOP Mode: 5 s
Constrained: Off

Figure B.24: Stream quality analysis for CostarHD RISE 4260HD Varying GOP Interval with Frame Rate test

	R_{nom}, R_{targ} (kbps)					
	512	768	1000	2000	4000	8000
	327	491	640	1280	2560	5120
352x240 @ 1 FPS	252 •••	240 ••••	249 ••••	251 ••••	242 ••••	253 ••••
352x240 @ 2 FPS	345 •••	424 •••	439 ••••	414 ••••	419 ••••	440 ••••
352x240 @ 5 FPS	342 •••	512 •••	672 •••	894 ••••	882 ••••	889 ••••
352x240 @ 15 FPS	352 •••	520 •••	674 •••	1353 •••	2218 •••	2225 ••••
352x240 @ 30 FPS	352 •••	529 •••	684 •••	1360 •••	2709 •••	4070 •••
720x480 @ 1 FPS	321 •••	514 •••	680 •••	1016 •••	1076 ••••	1044 ••••
720x480 @ 2 FPS	305 •••	464 •••	660 •••	1333 •••	1826 ••••	1867 ••••
720x480 @ 5 FPS	339 •••	509 •••	637 •••	1327 •••	2682 •••	3789 ••••
720x480 @ 15 FPS	349 •••	517 •••	687 •••	1361 •••	2710 •••	4570 •••
720x480 @ 30 FPS	347 •••	519 •••	680 •••	1348 •••	2716 •••	5395 •••
1280x720 @ 1 FPS	330 •••	486 •••	622 •••	1161 •••	2594 •••	2508 ••••
1280x720 @ 2 FPS	303 •••	438 •••	569 •••	1135 •••	2651 •••	4705 •••
1280x720 @ 5 FPS	334 •••	455 •••	613 •••	1157 •••	2549 •••	5429 •••
1280x720 @ 15 FPS	347 •••	523 •••	687 •••	1365 •••	2716 •••	5421 •••
1280x720 @ 30 FPS	355 •••	528 •••	686 •••	1363 •••	2719 •••	5429 •••
1920x1080 @ 1 FPS	338 •••	492 •••	611 •••	1233 •••	2517 •••	5331 •••
1920x1080 @ 2 FPS	289 •••	432 •••	561 •••	1097 •••	2279 •••	5312 •••
1920x1080 @ 5 FPS	297 •••	501 •••	623 •••	1159 •••	2219 •••	5166 •••
1920x1080 @ 15 FPS	376 •••	529 •••	684 •••	1358 •••	2702 •••	5419 •••
1920x1080 @ 30 FPS	532 •	575 •••	685 •••	1365 •••	2720 •••	5425 •••

R	:	measured average bitrate (kbps)
R_{nom}	:	nominal bitrate for link class (kbps)
R_{100}	:	net-limit test rate (100% of R_{nom})
R_{80}	:	net-limit test rate (80% of R_{nom})
R_{50}	:	net-limit test rate (50% of R_{nom})
R_{max}	:	specified max. rate (80% of R_{nom})
R_{targ}	:	specified target rate (80% of R_{max})
F_r	:	# frames received
F_e	:	# frames expected

R	:	$R \in [0,\ R_{targ}]$
R	:	$R \in (t,\ 1.25t]$
R	:	$R \in (1.25t,\ \infty)$
••••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	:	$F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	:	$F_r \div F_e \geq 90\%$ for R_{100}
•	:	$F_r \div F_e \geq 90\%$ for no test rates

Device:	Cohu 4261
Scene:	scene1
Encoding:	H264 Main CBR
GOP Mode:	30 f
Constrained:	On

Figure B.25: Stream quality analysis for CostarHD RISE 4260HD Constrained Mode test

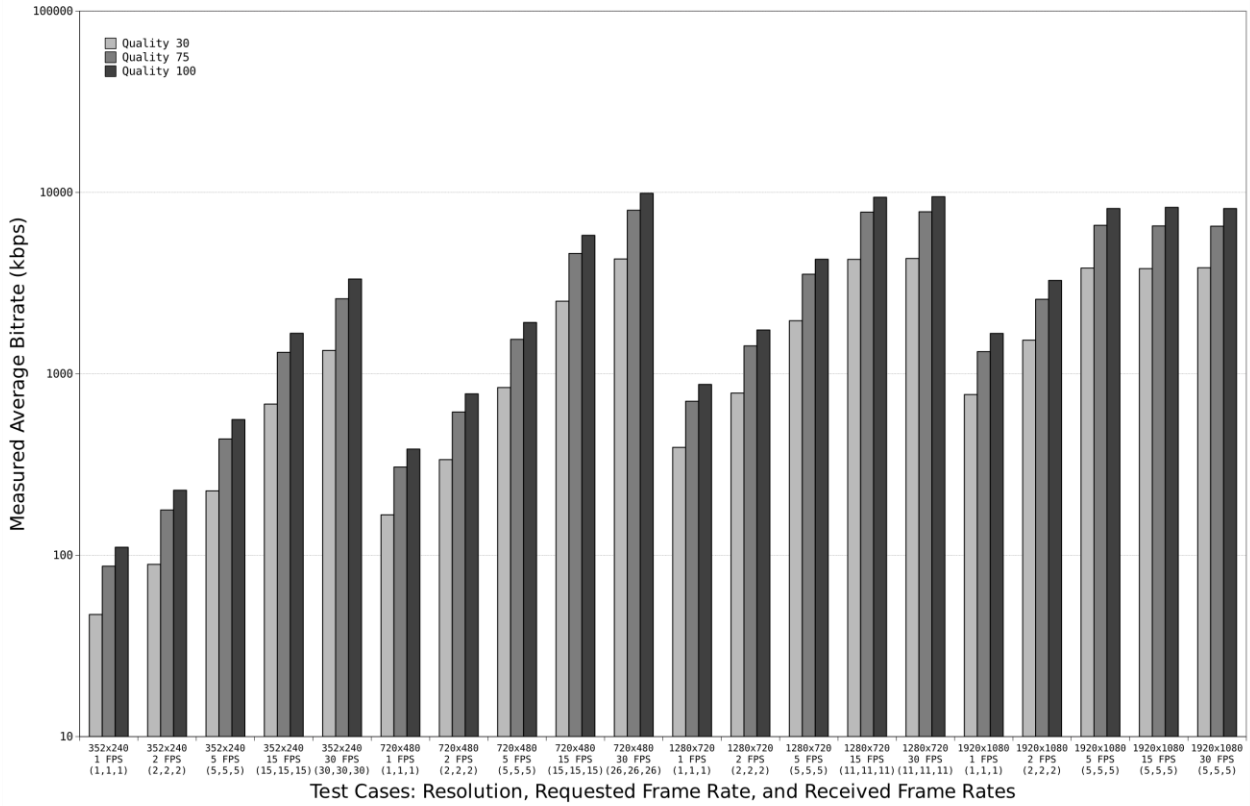

Figure B.26: Average bitrates for CostarHD RISE 4260HD M-JPEG test

	R_{nom}, R_{targ} (kbps)					
	512 327	768 491	1000 640	2000 1280	4000 2560	8000 5120
352x240 @ 1 FPS	264 •••	257 ••••	268 ••••	250 ••••	254 ••••	262 ••••
352x240 @ 2 FPS	343 •••	438 •••	437 ••••	459 ••••	443 ••••	463 ••••
352x240 @ 5 FPS	372 •••	555 •••	702 •••	975 ••••	973 ••••	980 ••••
352x240 @ 15 FPS	373 •••	557 •••	721 •••	1435 •••	2464 •••	2511 ••••
352x240 @ 30 FPS	379 •••	572 •••	725 •••	1438 •••	2851 •••	4207 •••
720x480 @ 1 FPS	332 •••	516 •••	676 •••	1053 •••	1082 ••••	1103 ••••
720x480 @ 2 FPS	297 •••	458 •••	627 •••	1381 •••	1939 ••••	1887 ••••
720x480 @ 5 FPS	348 ••	486 •••	648 •••	1413 •••	2799 •••	4228 ••••
720x480 @ 15 FPS	222 •	555 •••	723 •••	1429 •••	2845 •••	5629 •••
720x480 @ 30 FPS	57 •	561 •••	727 •••	1433 •••	2854 •••	5675 •••
1280x720 @ 1 FPS	137	485 •••	642 •••	1331 •••	2812 •	2587 ••••
1280x720 @ 2 FPS	30	436 •••	567 •••	1147 •••	2130 •	4750 •••
1280x720 @ 5 FPS	196 •	516 •••	649 •••	1247 •••	2655 •	5505 •••
1280x720 @ 15 FPS	78 •	555 •••	703 •••	1426 •••	1315 •	5592 •••
1280x720 @ 30 FPS	66 ••	561 •••	727 •••	1431 •••	697 ••••	5653 •••
1920x1080 @ 1 FPS	2	483 •••	614 •••	1234 •••	2257 •	5429 •••
1920x1080 @ 2 FPS	75 ••••	459 •••	561 •••	1137 •••	1201 •	5432 •••
1920x1080 @ 5 FPS	103 •	522 •••	691 •••	1203 •••	2534 •••	5587 •••
1920x1080 @ 15 FPS	63 •	554 •••	719 •••	1397 •••	2831 •••	5642 •••
1920x1080 @ 30 FPS	51 ••••	633 ••	716 •••	1420 •••	2835 •••	5646 •••

- R : measured average bitrate (kbps)
- R_{nom} : nominal bitrate for link class (kbps)
- R_{100} : net-limit test rate (100% of R_{nom})
- R_{80} : net-limit test rate (80% of R_{nom})
- R_{50} : net-limit test rate (50% of R_{nom})
- R_{max} : specified max. rate (80% of R_{nom})
- R_{targ} : specified target rate (80% of R_{max})
- F_r : # frames received
- F_e : # frames expected

R (green)	: $R \in [0, R_{targ}]$
R (yellow)	: $R \in (t, 1.25t]$
R (red)	: $R \in (1.25t, \infty)$
••••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	: $F_r \div F_e \geq 90\%$ for R_{100}
•	: $F_r \div F_e \geq 90\%$ for no test rates

Device: Cohu 4261
Scene: scene1
Encoding: H264 Main CBR
GOP Mode: 30 f
Constrained: Off

Figure B.27: Stream quality analysis for CostarHD RISE 4260HD TCP Streaming test

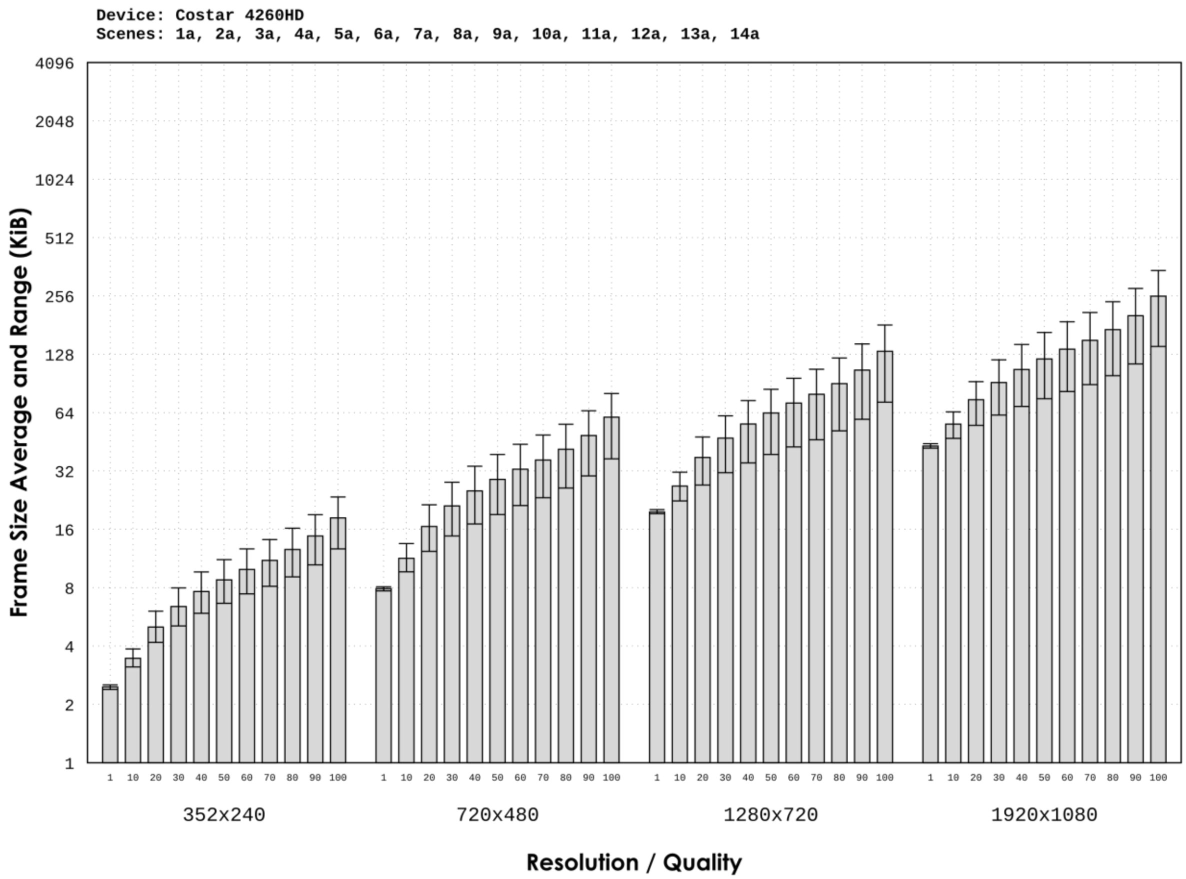

Figure B.28: Image sizes for CostarHD RISE 4260HD JPEG test

	R_{nom}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x240 @ 1 FPS	7 •	8 •	18 •••	22 •••	35 •••	77 •••	163 •••	334 •••	464 •	537 ••••	540 ••••	560 ••••	560 ••••
320x240 @ 2 FPS	15 •	16 •	19 ••	23 •••	37 •••	86 •••	168 •••	340 •••	516 •••	670 •••	1030 ••••	1007 ••••	1018 ••••
320x240 @ 5 FPS	27 •	29 •	28 •	27 •	37 •••	84 •••	171 •••	341 •••	511 •••	665 •••	1329 •••	2484 •••	2425 ••••
320x240 @ 15 FPS	62 •	60 •	58 •	56 •	51 •	87 •••	168 •••	338 •••	510 •••	662 •••	1320 •••	2641 •••	5269 •••
320x240 @ 30 FPS	102 •	103 •	67 •	94 •	84 •	104 •••	176 •••	342 •••	511 •••	667 •••	1324 •••	2642 •••	5269 •••
640x240 @ 1 FPS	19 •	19 •	19 •	19 •	32 •••	88 •••	169 ••	337 •••	485 •••	652 •••	1156 •••	1222 ••••	1201 ••••
640x240 @ 2 FPS	39 •	32 •	34 •	34 •	40 ••	85 •••	167 •••	335 •••	509 ••	651 •••	1314 •••	2407 •••	2314 ••••
640x240 @ 5 FPS	76 •	64 •	63 •	66 •	62 •	89 •••	168 •••	339 •••	512 •••	661 •••	1324 •••	2639 •••	5171 •••
640x240 @ 15 FPS	184 •	146 •	145 •	140 •	138 •	136 •	178 •••	338 •••	508 •••	661 •••	1318 •••	2636 •••	5288 •••
640x240 @ 30 FPS	267 •	264 •	246 •	31 •	249 •	219 •	330 •	353 •••	511 •••	666 •••	1323 •••	2641 •••	5267 •••
704x480 @ 1 FPS	29 •	31 •	31 •	29 •	33 ••	86 •••	169 ••	320 •••	454 •••	631 •••	1278 •••	2262 •••	2387 ••••
704x480 @ 2 FPS	56 •	53 •	56 •	55 •	56 •	84 •••	173 •••	340 •••	506 •••	683 •••	1327 •••	2703 •••	4647 •••
704x480 @ 5 FPS	105 •	97 •	105 •	105 •	103 •	107 ••	165 •••	337 •••	505 •••	661 •••	1335 •••	2638 •••	5256 •••
704x480 @ 15 FPS	215 •	213 •	199 •	202 •	197 •	212 •	226 ••	337 •••	506 •••	658 •••	1318 •••	2638 •••	5267 •••
704x480 @ 30 FPS	326 •	350 •	351 •	322 •	372 •	346 •	322 •	374 •••	513 •••	665 •••	1322 •••	2640 •••	5283 •••
1280x720 @ 1 FPS	77 •	78 •	68 •	73 •	77 •	77 •	150 •••	340 •••	512 •••	642 •••	1151 •••	2422 •••	4947 •••
1280x720 @ 2 FPS	136 •	137 •	142 •	138 •	141 •	144 •	168 •••	338 •••	496 •••	656 •••	1313 •••	2615 •••	5294 •••
1280x720 @ 5 FPS	262 •	267 •	264 •	262 •	260 •	268 •	257 •	346 •••	505 •••	657 •••	1320 •••	2633 •••	5263 •••
1280x720 @ 15 FPS	524 •	569 •	579 •	566 •	543 •	499 •	501 •	496 •	549 •••	670 •••	1317 •••	2638 •••	5285 •••
1280x720 @ 30 FPS	657 •	791 •	828 •	775 •	782 •	745 •	642 •	728 •	772 ••	780 ••	1333 •••	2643 •••	5280 •••
1920x1080 @ 1 FPS	147 •	128 •	133 •	131 •	123 •	123 •	123 ••	330 •••	474 •••	614 •••	1183 •••	2316 •••	4700 •••
1920x1080 @ 2 FPS	254 •	254 •	260 •	252 •	268 •	245 •	245 •	328 •••	510 •••	657 •••	1309 •••	2599 •••	5270 •••
1920x1080 @ 5 FPS	515 •	515 •	531 •	488 •	504 •	475 •	490 •	485 •	573 •••	669 •••	1319 •••	2640 •••	5286 •••
1920x1080 @ 15 FPS	989 •	917 •	945 •	971 •	985 •	923 •	902 •	920 •	941 •	963 •	1343 •••	2635 •••	5277 •••
1920x1080 @ 30 FPS	1880 •	1909 •	1902 •	1809 •	1797 ••	1729 •	1858 •	1753 •	1895 •	1740 •	2058 ••	2737 •••	5280 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R (green)	: $R \in [0, R_{targ}]$
R (yellow)	: $R \in (t, 1.25t]$
R (red)	: $R \in (1.25t, \infty)$
••••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	: $F_r \div F_e \geq 90\%$ for R_{100}
•	: $F_r \div F_e \geq 90\%$ for no test rates

Device: WTI SW720P
Scene: scene1
Encoding: h264main constant
GOP Mode: 30 f
Quality: 30

Figure B.29: Stream quality analysis for WTI Viper/Sidewinder HD Baseline (H.264 Main) test

	R_{nom}, R_{targ} (kbps)												
	9.6 6	14.4 9	28.8 18	33.6 21	56 35	128 81	256 163	512 327	768 491	1000 640	2000 1280	4000 2560	8000 5120
320x240 @ 1 FPS	7 •	7 •	19 •••	21 •	36 •••	85 •••	160 •••	307 •••	413 •••	414 ••••	433 ••••	426 ••••	426 ••••
320x240 @ 2 FPS	12 •	13 •	18 ••	22 ••	37 ••	86 •••	162 •••	328 •••	496 •••	662 •••	841 ••••	848 ••••	849 ••••
320x240 @ 5 FPS	21 •	21 •	23 ••	24 •••	37 •••	87 •••	171 •••	340 •••	504 •••	655 •••	1310 •••	1861 ••••	1874 ••••
320x240 @ 15 FPS	45 •	43 •	41 •	40 •	45 ••	87 •••	172 •••	341 •••	508 •••	664 •••	1320 •••	2635 •••	4961 •••
320x240 @ 30 FPS	74 •	69 •	63 •	63 •	65 •	95 •••	175 •••	341 •••	510 •••	665 •••	1323 •••	2645 •••	5277 •••
640x240 @ 1 FPS	15 •	15 •	15 ••	17 ••	37 ••	81 •••	169 •••	337 •••	481 •••	651 •••	906 ••••	859 ••••	923 ••••
640x240 @ 2 FPS	26 •	27 •	27 •	28 •	37 •	83 •••	168 •••	322 •••	487 •••	660 •••	1307 •••	1756 ••••	1838 ••••
640x240 @ 5 FPS	51 •	47 •	48 •	50 •	44 ••	84 •••	169 •••	340 •••	507 •••	659 •••	1309 •••	2646 •••	4160 ••••
640x240 @ 15 FPS	102 •	111 •	101 •	100 •	94 •	105 •••	173 •••	340 •••	509 •••	661 •••	1319 •••	2637 •••	5268 •••
640x240 @ 30 FPS	170 •	166 •	167 •	163 ••	140 •	155 •	189 •••	341 •••	510 •••	663 •••	1321 •••	2639 •••	5277 •••
704x480 @ 1 FPS	23 •	21 •	23 •	23 •	33 ••	83 •••	168 •••	325 •••	494 •••	614 •••	1266 •••	1770 ••••	1807 ••••
704x480 @ 2 FPS	43 •	43 •	43 •	42 •	44 ••	84 •••	173 •••	343 •••	503 •••	658 •••	1328 ••	2627 •••	3563 ••••
704x480 @ 5 FPS	77 •	74 •	73 •	76 •	75 •	97 •••	168 •••	344 •••	513 •••	668 •••	1324 •••	2639 •••	5278 •••
704x480 @ 15 FPS	161 •	157 •	155 •	158 •	154 •	155 •	183 •••	346 •••	510 •••	663 •••	1321 •••	2634 •••	5278 •••
704x480 @ 30 FPS	234 •	254 •	252 •	239 •	251 •	250 •	246 ••	348 •••	509 •••	661 •••	1320 •••	2637 •••	5274 •••
1280x720 @ 1 FPS	56 •	59 •	60 •	60 •	59 •	64 •••	166 •••	328 •••	491 •••	640 •••	1311 •••	2471 •••	5138 •••
1280x720 @ 2 FPS	113 •	116 •	109 •	113 •	116 •	113 •	173 •••	334 •••	499 •••	677 •••	1292 •••	2577 •••	5319 •••
1280x720 @ 5 FPS	213 •	210 •	211 •	209 •	217 •	219 •	198 ••	342 •••	523 •••	669 •••	1328 •••	2644 •••	5285 •••
1280x720 @ 15 FPS	441 •	443 •	414 •	428 •	442 •	424 •	412 •	424 ••	525 •••	670 •••	1325 •••	2643 •••	5264 •••
1280x720 @ 30 FPS	655 •	641 •	680 •	669 •	660 •	679 •	641 •	593 •	628 •••	711 •••	1311 •••	2632 •••	5281 •••
1920x1080 @ 1 FPS	123 •	126 •	121 •	126 •	122 •	122 •	131 •••	328 •••	490 •••	618 ••	1209 •••	2508 •••	4996 •••
1920x1080 @ 2 FPS	221 •	236 •	230 •	233 •	233 •	226 •	225 ••	345 •••	504 •••	661 •••	1352 •••	2665 •••	5348 •••
1920x1080 @ 5 FPS	425 •	427 •	452 •	266 •	455 •	442 •	422 •	435 ••	524 •••	666 •••	1323 •••	2669 •••	5277 •••
1920x1080 @ 15 FPS	853 •	849 •	855 •	896 •	887 •	484 •	850 •	810 •	808 •	906 ••	1325 •••	2639 •••	5280 •••
1920x1080 @ 30 FPS	1653 •	1700 •	1696 •	1665 •	1711 •	1655 •	1668 •	1531 •	1615 •	1662 •	1692 ••	2631 •••	5269 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0, R_{targ}]$
R : $R \in (t, 1.25t]$
R : $R \in (1.25t, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: WTI SW720P
Scene: scene1
Encoding: h264high constant
GOP Mode: 30 f
Quality: 30

Figure B.30: Stream quality analysis for WTI Viper/Sidewinder HD H.264 High Profile test

	R_{nom}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x240 @ 1 FPS	9 •	9 •	17 •••	22 ••	36 •••	78 •••	162 •••	315 •••	499 •••	580 •••	558 ••••	597 ••••	592 ••••
320x240 @ 2 FPS	17 •	17 •	20 •	23 ••	36 •••	86 •••	168 •••	348 •••	498 •••	659 •••	1153 •••	1160 ••••	1147 ••••
320x240 @ 5 FPS	29 •	30 •	32 •	33 •	38 •••	85 •••	169 •••	338 •••	509 •••	648 •••	1317 •••	2623 •••	2605 ••••
320x240 @ 15 FPS	64 •	70 •	74 •	73 •	61 •	87 •••	169 •••	339 •••	507 •••	662 •••	1322 •••	2633 •••	5294 •••
320x240 @ 30 FPS	101 •	113 •	128 •	128 •	102 •	104 •••	176 •••	342 •••	509 •••	663 •••	1322 •••	2641 •••	5272 •••
640x240 @ 1 FPS	23 •	23 •	23 •	23 •	31 •••	79 •••	159 •••	319 •••	493 •••	603 •••	1292 •••	1273 ••••	1257 ••••
640x240 @ 2 FPS	46 •	45 •	45 •	37 •	36 ••	84 •••	163 •••	335 •••	513 •••	666 •••	1320 •••	2384 •••	2396 ••••
640x240 @ 5 FPS	88 •	87 •	84 •	77 •	70 •	90 •••	170 •••	336 •••	507 •••	663 •••	1319 •••	2653 •••	5261 •••
640x240 @ 15 FPS	213 •	234 •	216 •	217 •	174 •	162 •	190 •••	338 •••	506 •••	660 •••	1320 •••	2646 •••	5283 •••
640x240 @ 30 FPS	313 •	392 •	436 •	396 •	338 •	244 •	259 •	359 •••	531 •••	663 •••	1323 •••	2628 •••	5275 •••
704x480 @ 1 FPS	34 •	37 •	31 •	33 •	33 •	84 •••	168 •••	319 •••	478 •••	652 •	1172 •••	2450 •••	2367 ••••
704x480 @ 2 FPS	68 •	64 •	61 •	60 •	57 •	83 •••	172 •••	333 •••	509 •••	658 •••	1316 ••	2601 •••	4732 •••
704x480 @ 5 FPS	120 •	117 •	116 •	119 •	112 •	109 ••	168 •••	338 •••	507 •••	663 •••	1317 •••	2631 •••	5293 •••
704x480 @ 15 FPS	252 •	261 •	244 •	254 •	248 •	216 •	217 ••	340 •••	507 •••	658 •••	1320 •••	2638 •••	5284 •••
704x480 @ 30 FPS	389 •	434 •	409 •	426 •	364 •	330 •	365 •	402 •••	531 •••	662 •••	1325 •••	2635 •••	5270 •••
1280x720 @ 1 FPS	82 •	84 •	85 •	89 •	83 •	74 •	147 •••	305 •••	507 •••	647 •••	1271 •	2325 •••	4953 •••
1280x720 @ 2 FPS	165 •	169 •	159 •	163 •	150 •	153 •	168 •••	329 •••	503 •••	669 •••	1318 •••	2633 •••	5254 •••
1280x720 @ 5 FPS	320 •	322 •	302 •	303 •	283 •	281 •	282 •	380 •••	507 •••	646 •••	1306 •••	2664 •••	5265 •••
1280x720 @ 15 FPS	603 •	617 •	634 •	633 •	569 •	581 •	571 •	621 •	632 •••	714 •••	1316 •••	2634 •••	5275 •••
1280x720 @ 30 FPS	914 •	936 •	917 •	871 •	886 •	828 •	836 •	956 •	893 •	961 ••	1332 •••	2645 •••	5273 •••
1920x1080 @ 1 FPS	154 •	170 •	165 •	151 •	139 •	159 •	139 ••	316 •••	484 •••	602 •••	1229 •••	2383 ••	4702 •••
1920x1080 @ 2 FPS	295 •	303 •	303 •	309 •	287 •	288 •	279 •	313 •••	511 •••	663 •••	1279 •••	2619 •••	5242 •••
1920x1080 @ 5 FPS	585 •	608 •	600 •	594 •	575 •	572 •	574 •	607 •	621 ••	737 •••	1315 •••	2647 •••	5303 •••
1920x1080 @ 15 FPS	1128 •	1172 •	1145 •	1203 •	1074 •	1145 •	1077 •	1172 •	1146 •	1141 •	1399 •••	2634 •••	5274 •••
1920x1080 @ 30 FPS	2346 •	2375 •	2469 •	2516 •	2421 •	2323 •	2295 •	2543 •	2363 •	2435 •	2527 •	2856 •••	5283 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R	: $R \in [0, R_{targ}]$
R	: $R \in (t, 1.25t]$
R	: $R \in (1.25t, \infty)$
••••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	: $F_r \div F_e \geq 90\%$ for R_{100}
•	: $F_r \div F_e \geq 90\%$ for no test rates

Device: WTI SW720P
Scene: scene1
Encoding: h264base constant
GOP Mode: 30 f
Quality: 30

Figure B.31: Stream quality analysis for WTI Viper/Sidewinder HD H.264 Baseline Profile test

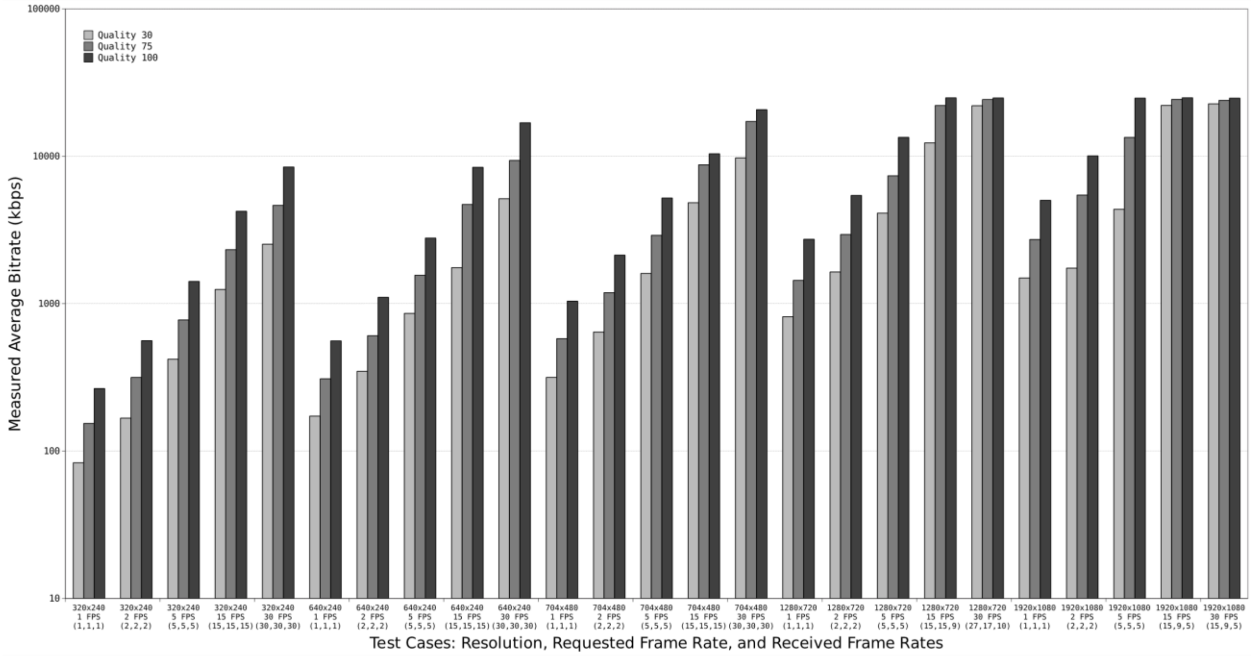

Figure B.32: Average bitrates for WTI Viper/Sidewinder HD M-JPEG test

	R_{nom}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x240 @ 1 FPS	13 •	13 •	19 ••	19 ••	37 •••	85 •••	171 •••	315 •••	434 •••	513 ••••	556 ••••	569 ••••	567 ••••
320x240 @ 2 FPS	19 •	19 •	20 •	22 ••	39 •••	81 •••	175 •••	330 •••	516 •••	654 •••	1043 ••••	1052 ••••	1058 ••••
320x240 @ 5 FPS	28 •	29 •	28 •	29 •	37 •••	81 •••	168 •••	339 •••	508 •••	655 •••	1312 •••	2415 •••	2414 ••••
320x240 @ 15 FPS	52 •	52 •	53 •	48 •	50 •	86 •••	170 •••	339 •••	509 •••	661 •••	1320 •••	2634 •••	5265 •••
320x240 @ 30 FPS	77 •	76 •	73 •	72 •	78 •	99 •••	173 •••	340 •••	510 •••	664 •••	1324 •••	2643 •••	5276 •••
640x240 @ 1 FPS	28 •	28 •	29 •	28 •	32 •••	78 •••	152 •••	340 •••	456 •••	626 •••	1100 •••	1163 ••••	1178 ••••
640x240 @ 2 FPS	39 •	39 •	42 •	41 •	42 ••	88 •••	178 •••	335 •••	510 •••	656 •••	1330 •••	2229 •••	2319 ••••
640x240 @ 5 FPS	66 •	68 •	64 •	65 •	70 •	86 •••	168 •••	338 •••	507 •••	661 •••	1307 •••	2625 •••	5290 •••
640x240 @ 15 FPS	132 •	136 •	136 •	135 •	127 •	126 •	172 •••	339 •••	508 •••	660 •••	1320 •••	2634 •••	5254 •••
640x240 @ 30 FPS	204 •	191 •	193 •	195 •	200 •	199 •	210 •••	340 •••	510 •••	663 •••	1321 •••	2642 •••	5270 •••
704x480 @ 1 FPS	46 •	45 •	46 •	47 •	47 •	82 •••	179 •••	333 •••	503 •••	643 •••	1227 •••	2203 •••	2349 ••••
704x480 @ 2 FPS	65 •	67 •	67 •	67 •	71 •	86 •••	168 •••	345 •••	532 •••	641 •••	1332 •••	2606 •	4597 •••
704x480 @ 5 FPS	109 •	109 •	108 •	105 •	108 •	109 ••	160 •••	336 •••	514 •••	652 •••	1328 •••	2614 •••	5244 •••
704x480 @ 15 FPS	180 •	181 •	182 •	184 •	182 •	183 •	194 •••	339 •••	508 •••	661 •••	1320 •••	2641 •••	5275 •••
704x480 @ 30 FPS	288 •	254 •	255 •	253 •	280 •	237 •	271 •	359 •••	510 •••	663 •••	1322 •••	2642 •••	5277 •••
1280x720 @ 1 FPS	105 •	104 •	112 •	110 •	114 •	109 •	159 •••	338 •••	524 •••	685 •••	1340 •••	2402 •••	4972 •••
1280x720 @ 2 FPS	168 •	160 •	168 •	164 •	164 •	161 ••	168 •••	351 •••	514 •••	667 •••	1348 •••	2648 •••	5422 •••
1280x720 @ 5 FPS	289 •	284 •	271 •	274 •	275 •	260 •	256 •	352 •••	483 •••	654 •••	1306 •••	2633 •••	5254 •••
1280x720 @ 15 FPS	478 •	511 •	467 •	501 •	501 •	475 •	209 •	444 •••	547 •••	677 •••	1322 •••	2641 •••	5283 •••
1280x720 @ 30 FPS	628 •	615 •	642 •	660 •	634 •	590 •	602 •	359 •	597 •••	754 •••	1321 •••	2642 •••	5278 •••
1920x1080 @ 1 FPS	192 •	189 •	190 •	191 •	194 •	192 •	190 ••	344 •••	540 •••	681 •••	1340 •••	2423 •••	5072 •
1920x1080 @ 2 FPS	296 •	300 •	299 •	297 •	309 •	290 •	304 •	358 •••	532 •••	673 •••	1350 •••	2691 •••	5353 ••
1920x1080 @ 5 FPS	517 •	499 •	514 •	502 •	493 •	481 •	484 •	493 •	577 •••	652 •••	1302 •••	2605 •••	5271 •••
1920x1080 @ 15 FPS	895 •	912 •	914 •	898 •	919 •	838 •	859 •	890 •	921 ••	952 •	1347 •••	2635 •••	5278 •••
1920x1080 @ 30 FPS	2106 •	1968 •	2045 •	2042 •	2040 •	1868 •	1810 •	1802 •	1880 •	1868 •	1988 ••	2639 •••	5279 •••

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R : $R \in [0, R_{targ}]$
R : $R \in (t, 1.25t]$
R : $R \in (1.25t, \infty)$
•••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
••• : $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
•• : $F_r \div F_e \geq 90\%$ for R_{100}
• : $F_r \div F_e \geq 90\%$ for no test rates

Device: WTI SW720P
Scene: scene1
Encoding: h264main constant
GOP Mode: 5 s
Quality: 30

Figure B.33: Stream quality analysis for WTI Viper/Sidewinder HD Varying GOP Interval with Frame Rate test

	R_{nom}, R_{targ} (kbps)												
	9.6	14.4	28.8	33.6	56	128	256	512	768	1000	2000	4000	8000
	6	9	18	21	35	81	163	327	491	640	1280	2560	5120
320x240 @ 1 FPS	9 •	8 •	16 •••	23 •••	33 •••	83 •••	177 •••	280 •••	400 •••	420 ••••	436 ••••	562 ••••	418 ••••
320x240 @ 2 FPS	16 •	16 •	1 ••••	23 ••	32 •••	74 •••	147 •••	294 •••	433 •••	591 ••	879 ••••	1117 ••••	880 ••••
320x240 @ 5 FPS	27 •	28 •	1 ••••	30 •	35 •••	0 ••••	181 •••	296 •••	453 •••	583 •••	1162 •••	2622 •••	2162 ••••
320x240 @ 15 FPS	56 •	56 •	71 •	65 •	54 •••	83 •••	185 •••	306 •••	452 •••	696 •••	1169 •••	2766 •••	4661 •
320x240 @ 30 FPS	102 •	0 •••	105 •	0 ••••	7 •••	1 ••••	167 •••	310 •••	455 •••	697 •••	1160 •••	2741 •••	4603 •
640x240 @ 1 FPS	1 •	20 •	19 •	16 ••	28 •••	75 •••	129 •••	258 ••	384 •••	665 •••	955 •••	996 ••••	1279 ••••
640x240 @ 2 FPS	1 •	26 •	39 •	0 ••••	32 •••	75 •••	178 •••	294 •••	442 •••	690 •••	1142 •••	1966 •	2327 ••
640x240 @ 5 FPS	50 •	56 •	59 •	1 ••••	54 ••	78 •••	149 •••	299 •••	447 •••	696 •••	1163 •••	2352 ••	4594 •
640x240 @ 15 FPS	0 •	121 •	195 •	129 •	1 ••••	0 ••••	164 •••	304 •••	452 •••	696 •••	1164 •••	2342 •••	4623 •
640x240 @ 30 FPS	217 •	229 •	324 •	234 •	251 •	230 •	243 •	320 •••	455 •••	696 •••	1157 •••	2331 •••	4601 •
704x480 @ 1 FPS	31 •	31 •	29 •	33 •	33 •	67 ••	167 ••	280 ••	412 •••	606 •••	1037 •••	1682 •••	1932 ••••
704x480 @ 2 FPS	1 •	24 •	51 •	60 •	62 •	0 •	178 •	302 ••	447 •••	713 •••	1174 •••	2303 •••	4001 •••
704x480 @ 5 FPS	100 •	97 •	90 •	82 •	111 •	0 ••••	177 ••	299 •••	452 •••	697 •••	1170 •••	2316 •••	5531 •
704x480 @ 15 FPS	1 •	1 •••	192 •	176 •	226 •	0 ••••	235 ••	305 ••	450 •••	698 •••	1166 •••	2338 •••	5538 •
704x480 @ 30 FPS	275 •	375 •	344 •	291 •	349 •	347 •	344 •	343 ••	459 •••	694 •••	1160 •••	2314 •••	4631 •
1280x720 @ 1 FPS	75 •	74 •	64 •	62 •	81 •	69 •	159 •	277 •	386 ••	659 •••	971 •••	2108 •••	4341 •••
1280x720 @ 2 FPS	123 •	113 •	121 •	146 •	128 •	124 •	163 •	292 •	443 •••	694 •••	1135 •••	2358 •	4666 •
1280x720 @ 5 FPS	253 •	220 •	287 •	284 •	230 •	217 •	283 •	307 •	447 •••	704 •••	1171 •••	2348 •••	4629 •
1280x720 @ 15 FPS	522 •	535 •	492 •	558 •	454 •	449 •	564 •	492 ••	519 •••	704 •••	1172 •••	2321 •••	4639 •
1280x720 @ 30 FPS	783 •	773 •	829 •	841 •	832 •	798 •	801 •	824 •	772 •	697 •	1369 •••	2754 •••	5510 •
1920x1080 @ 1 FPS	134 •	107 •	110 •	141 •	104 •	107 •	106 •	335 •	404 ••	657 •••	1339 •••	2642 •••	5083 •
1920x1080 @ 2 FPS	274 •	272 •	289 •	279 •	229 •	289 •	235 •	363 •	542 •••	718 •••	1392 •••	2799 ••	5646 •
1920x1080 @ 5 FPS	425 •	512 •	435 •	532 •	431 •	414 •	419 •	538 •	605 •••	709 •••	1393 •••	2308 •••	5494 •
1920x1080 @ 15 FPS	954 •	923 •	1002 •	1005 •	836 •	1065 •	844 •	992 •	969 •	980 •	1390 •••	2328 •••	5527 •
1920x1080 @ 30 FPS	1814 •	1897 •	1995 •	2080 •	2265 •	2182 •	1936 •	2325 •	2094 •	1941 •	1957 ••	2336 •••	5537 •

R : measured average bitrate (kbps)
R_{nom} : nominal bitrate for link class (kbps)
R_{100} : net-limit test rate (100% of R_{nom})
R_{80} : net-limit test rate (80% of R_{nom})
R_{50} : net-limit test rate (50% of R_{nom})
R_{max} : specified max. rate (80% of R_{nom})
R_{targ} : specified target rate (80% of R_{max})
F_r : # frames received
F_e : # frames expected

R (green)	: $R \in [0, R_{targ}]$
R (yellow)	: $R \in (t, 1.25t]$
R (red)	: $R \in (1.25t, \infty)$
••••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}, R_{50}
•••	: $F_r \div F_e \geq 90\%$ for R_{100}, R_{80}
••	: $F_r \div F_e \geq 90\%$ for R_{100}
•	: $F_r \div F_e \geq 90\%$ for no test rates

Device: WTI SW720P
Scene: scene1
Encoding: h264main constant
GOP Mode: 30 f
Quality: 30

Figure B.34: Stream quality analysis for WTI Viper/Sidewinder HD TCP Streaming test

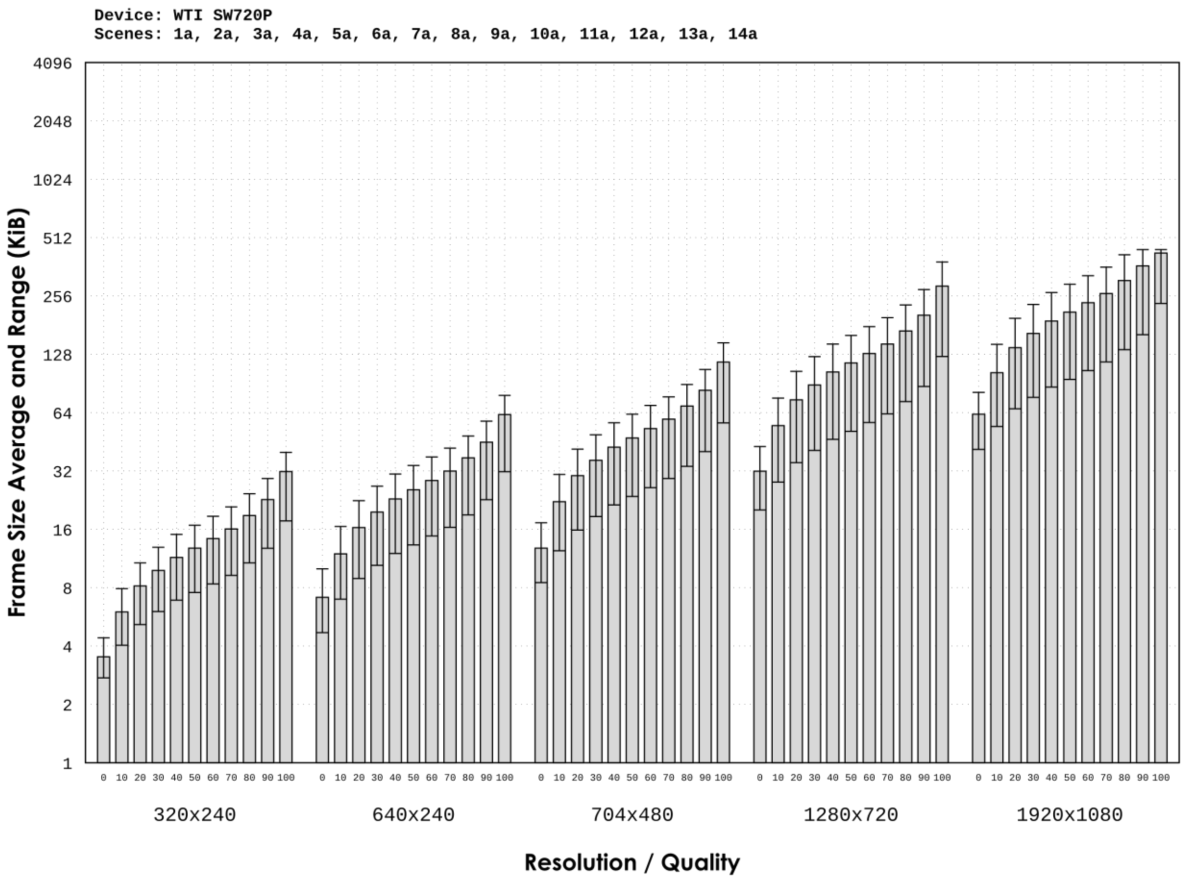

Figure B.35: Image sizes for WTI Viper/Sidewinder HD JPEG test