Mobile-Health Systems Use Diagnostically Driven Medical Video Technologies [Life Sciences]

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Mobile-Health Systems Use Diagnostically Driven Medical Video Technologies

Mobile-health (m-health) systems and services are expected to undergo significant growth in the near future [1]–[4]. Based on recent advances in signal and video processing and communications technologies, m-health systems and services are driven by greater socioeconomic aspects aiming to bridge society's demands for specialized health-care delivery.

Figure 1 depicts typical application scenarios of m-health systems and services. This comprises m-health medical video communication systems, remote monitoring for personal health based on body area networks, disaster crisis management, electronic health records, m-health cloud-based services, and smartphone applications.

Medical video communication is a key bandwidth-demanding component of m-health applications ranging from emergency incidents response, to home monitoring, and medical education. In-ambulance video (trauma and ultrasound) communication for remote diagnosis and care can provide significant time savings that in turn can prove decisive for the patient's survival. Similarly, emergency scenery video can assist in better triage and preparatory hospital processes. Remote diagnosis allows access to specialized care for people residing in remote areas, but also for the elderly, and people with chronic diseases and mobility problems. Moreover, it can support mass population screening and second opinion provision, especially in developing countries. Medical education also benefits from real-time surgery video transmission as well as ultrasound examinations.

Overall, wireless medical video communication poses significant challenges that stem from limited bandwidths over noisy channels. In terms of both bandwidth and processing requirements, medical videos dominate over other biomedical signals. Clearly, the wider application of future m-health systems will depend and also benefit from the development of effective medical video communication systems, extending current systems that support real-time and continuous monitoring of biosignals.

m-HEALTH MEDICAL VIDEO COMMUNICATIONS: THE PROMISE THAT LIES AHEAD

M-health medical video communication systems advances have been primarily driven by associated advancements in wireless networks and video compression technologies [5]. Early second-and-a-half-generation (2.5G) wireless networks enabled a breakthrough shift from biomedical signal to image and video communications. The introduction of third-generation (3G) and third-and-a-half-generation (3.5G) of mobile communication networks supported a transition from low-bit rate video of limited clinical capacity (and hence interest) to higher diagnostic quality medical video. The latter was largely attributed to analogous developments in video compression. Emerging video coding standards provided significant compression efficiency, the error-resiliency tools for robust communications over error-prone wireless channels, and ultimately network-independent encoding (introduced in H.264/Advanced Video Coding (AVC). Table 1 summarizes selected m-health video communication systems. Earlier studies employ video coding standards such as motion-JPEG, MPEG2, and H.263, while recent studies rely on the H.264/AVC standard. The use of H.264/AVC codec together with 3.5G mobile Worldwide Interoperability for Microwave Access (WiMAX) and High-Speed Packet Access (Plus) [HSPA(+)] wireless networks (see also Figure 1) allow high resolution and high frame rate medical video communication. As a result, adequate clinical capacity medical video is feasible for a number of remote clinical application scenarios. Yet, in contradiction to initial expectations and enthusiasm, there has been little adoption in standard clinical practice.

The new High-Efficiency Video Coding (HEVC) standard [6], together with fourth-generation (4G) wireless networks deployment, is expected to play a decisive role toward wider adoption. New m-health video systems that can rival the standards of in-hospital examinations are envisioned. Wider adoption will result from the use of medical video communication at the clinically acquired resolution and frame rate that can be robustly transmitted in low delay without compromising clinical quality.

THE NEED FOR DIAGNOSTICALLY DRIVEN SYSTEMS

Compared to standard approaches in wireless video communications, m-health systems need to be diagnostically driven. This notion is derived from the objective of delivering medical video of adequate diagnostic quality. The latter differs from a focus on perceptual quality of conventional video, often termed *subjective quality*. Clinical quality cannot be compromised. Furthermore, appropriate

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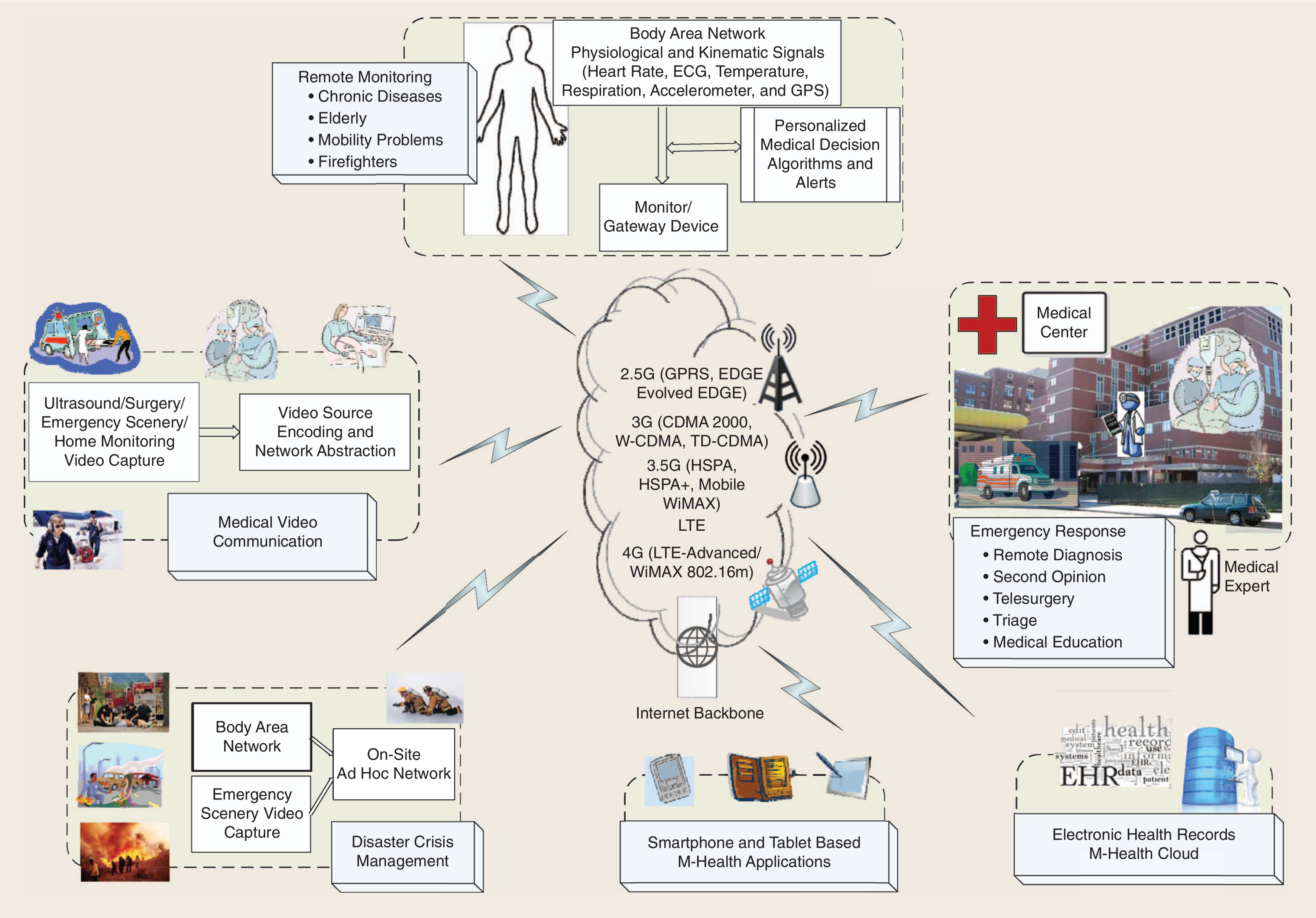


[FIG1] **The selected m-Health systems and services range from medical video communications and remote monitoring, to emergency response and disaster crisis management, and electronic health records and m-health cloud, smartphone- and tablet-based applications.**

[TABLE 1] SELECTED m-HEALTH MEDICAL VIDEO COMMUNICATION SYSTEMS.

	AUTHOR	YEAR	RESOLUTION, FRAME RATE, BITRATE	ENCODING STANDARD	WIRELESS NETWORK	MEDICAL VIDEO MODALITY
NONDIAGNOSTICALLY DRIVEN SYSTEMS	CHU ET AL. [17][2]	04	{320 ×240 AND 160 × 120} <5 FRAMES/S 50–80 Kb/s	M-JPEG	3G-CDMA	TRAUMA VIDEO
	GARAWI ET AL. [18][2,3]	06	176 × 144 @ 5 FRAMES/S 18.5–60 Kb/s	H.263	3G-UMTS	CARDIAC ULTRASOUND
	ALINEJAD ET AL. [16][2]	12	{176 × 144, 352 × 288} @ 10/20 FRAMES/S {220, 430} Kb/s, 1.3 Mb/s	WINDOWS MEDIA VIDEO (WMV)	MOBILE WIMAX, HSDPA	CARDIAC ULTRASOUND
	ISTEPANIAN ET AL. [19][2,3]	09	176 × 144 @ 8–10 FRAMES/S 50–130 Kb/s	H.264/ AVC	3G	ABDOMEN ULTRASOUND
	PANAYIDES ET AL. [20][2,3]	13	{176 × 144, 352 × 288, 560 × 416} @ 15 FRAMES/S, 64–768 Kb/s	H.264/AVC	HSPA	CAROTID ARTERY ULTRASOUND
	PANAYIDES ET AL. [6][1,3]	13	560 × 416 @ 40 FRAMES/S, UP TO 2 Mb/s	HEVC	3.5G AND BEYOND	CAROTID ARTERY ULTRASOUND
DIAGNOSTICALLY DRIVEN SYSTEMS	RAO ET AL. [8][1,3,4]	09	360 × 240 @ 30 FRAMES/S 500 Kb/s	MPEG-2	3G AND BEYOND	PEDIATRIC RESPIRATORY DISTRESS RELATED VIDEOS
	MARTINI ET AL. [9][1,4]	10	480 × 256@15 FRAMES/S 300 Kb/s	H.264/AVC	MOBILE WiMAX	CARDIAC ULTRASOUND
	PANAYIDES ET AL. [10][1,3,4]	11	352 × 288 @ 15 FPS 197–421 Kb/s	H.264/AVC	3G AND BEYOND	CAROTID ARTERY ULTRASOUND
	KHIRE ET AL. [12][2,3,4]	12	720 × 480 @ 30 FRAMES/S, 125–200 Kb/s	H.264/AVC	3G AND BEYOND	MAXILLOFACIAL SURGERY CLIPS
	DEBONO ET AL. [14][1,4]	12	640 × 480 @ 25 FRAMES/S	H.264/AVC	MOBILE WiMAX	CARDIAC ULTRASOUND
	PANAYIDES ET AL. [11][2,3,4]	13	704 × 576@15 FRAMES/S 768 Kb/s–1.5 Mb/s	H.264/AVC	MOBILE WiMAX	CAROTID ARTERY ULTRASOUND
	CAVERO ET AL. [13][1,3]	13	720 × 576 @ 25 FRAMES/S 40 Kb/s (M-MODE), 200 Kb/s (B-MODE)	SPIHT	3G AND BEYOND	CARDIAC ULTRASOUND
	CAVERO ET AL. [15][1,3]	12	720 × 576 @ 25 FRAMES/S, 200 Kb/s	SPIHT	HSUPA, MOBILE WiMAX	CARDIAC ULTRASOUND

[1]Simulation, [2]Real Time, [3]Clinical Evaluation, [4]d-ROI.

clinical protocols need to be established so as to guarantee that the communicated video evaluated by the remote medical expert is of the same diagnostic quality as the one displayed on the in-hospital machine screen. As a result, incorporated methods for video compression, wireless transmission, and clinical video quality assessment (c-VQA) are developed exploiting the clinical aspect of the underlying medical video modality. The aim is to maximize the clinical capacity of the communicated video. Toward this end, diagnostically driven approaches are not always universally applicable; rather they are often medical video modality specific.

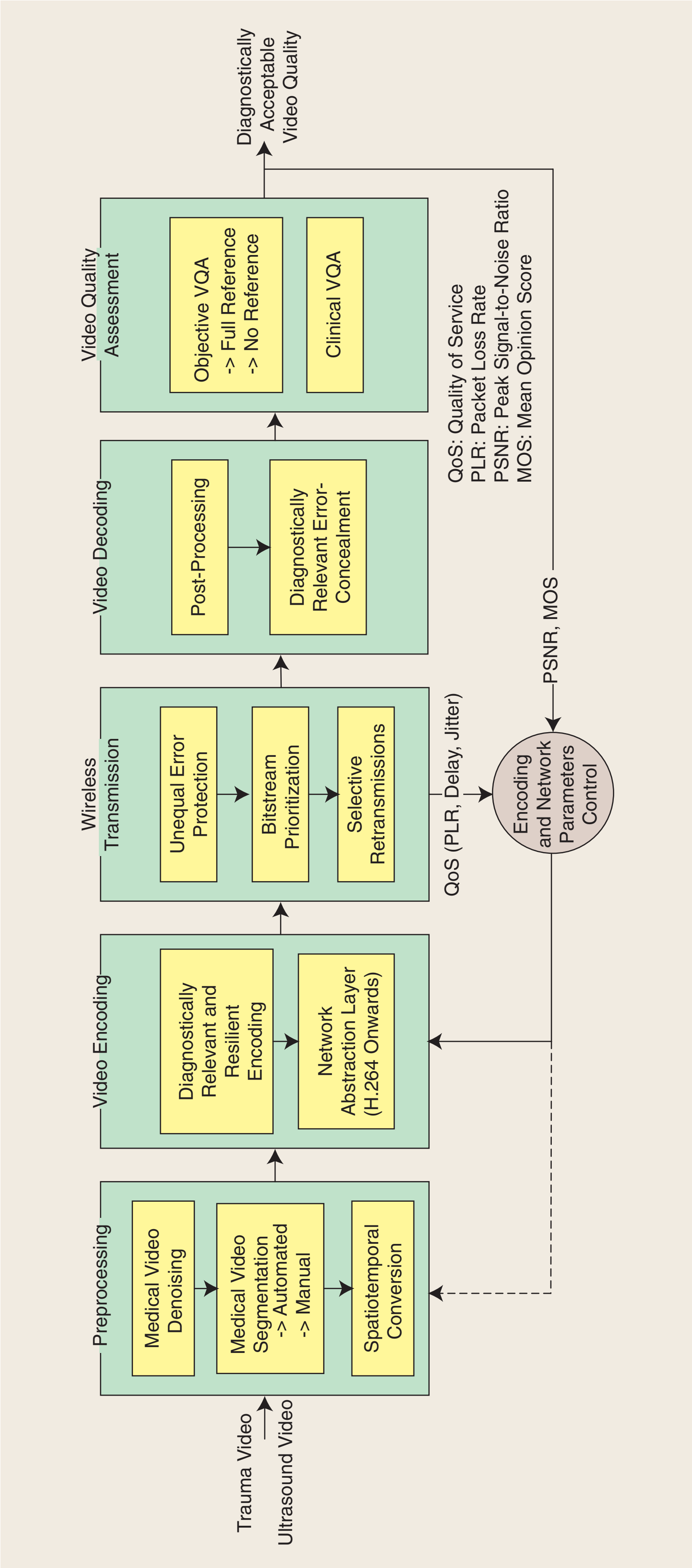
Figure 2 summarizes a diagnostically driven medical video communication framework. Following preprocessing steps, diagnostically relevant encoding takes place. Wireless transmission prioritizes the communicated video bitstream compared to less demanding applications. At the receiver's side, postprocessing and diagnostically relevant decoding precedes video quality assessment (VQA). Where applicable, adaptation to the varying wireless network state is performed, using quality-of-service (QoS) and c-VQA measurements, to preserve the communicated video's clinical standards. The latter approach, excluding the wireless network component, is used for fine tuning diagnostically acceptable source encoding parameters, including video resolution, frame rate, and quantization factor.

PREPROCESSING

Preprocessing can involve the use of denoising, the identification of diagnostic regions-of-interest (d-ROI), and spatiotemporal conversion (see Figure 2). The use of denoising as a method for saving communications bandwidth is an emerging area of research. For example, in [7], we report on the use of an ultrasound despeckling method that can improve the overall video quality as well as significantly reduce bandwidth requirements. The identification of d-ROI has become a standard component of effective medical video compression systems [8]–[12]. Depending on the available bandwidth and end-user device equipment, preprocessing may also involve a spatiotemporal (video resolution and frame rate) conversion.

DIAGOSTICALLY RELEVANT ENCODING

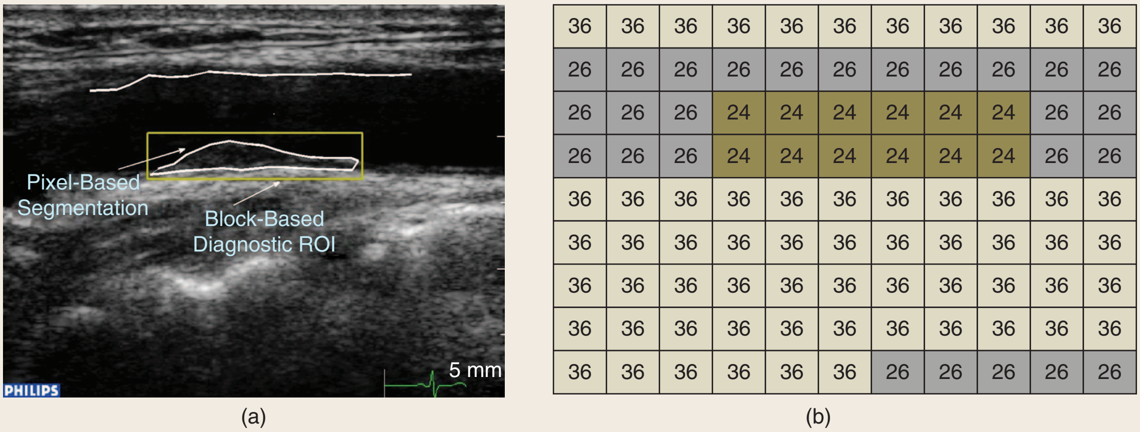
Diagnostically relevant encoding systems refer to systems that adapt the encoding process to cater for different properties of different medical video modalities (see Table 1). One of the most prevailing techniques is found in d-ROI-based systems.



[FIG2] **A medical video communication system diagram. Following preprocessing, diagnostically driven video encoding adapts to each medical video modality. Wireless transmission protects more strongly the clinically sensitive regions. At the receiver's side, diagnostically relevant error concealment is performed, followed by objective and clinical VQA. Cross-layer information is used to adapt to the underlying wireless network's varying state.**

The key concept is that certain regions in the video carry specific clinical information assessed by the medical expert during diagnosis. These d-ROI can be further associated with the assessment of different clinical criteria and therefore categorized with respect to (incremental) diagnostic significance and/or difficulty of the evaluation process. A well-known method is variable quality slice encoding, which assigns quality levels as a function of the region's diagnostic significance (see Figure 3 and the section "Case Study"). Significant bandwidth reductions can be achieved by using high levels of compression on the background, or nondiagnostically important regions. On the other hand, very low compression levels are used on d-ROI that have to maintain high diagnostic quality. This technique has been adopted for respiratory distress related video [8], cardiac ultrasound [9], common carotid artery ultrasound [10], [11,] and maxillofacial surgery clips [12] (see Table 1). The authors in [13] exploit cardiac ultrasound properties to design an encoding scheme, which also minimizes bit rate requirements for equivalent clinical quality.

Diagnostically resilient encoding adapts existing error-resilient methods in favor of the diagnostic capacity of the communicated medical video. In this sense, intraupdating intervals can be tailored to match the periodicity of the cardiac cycle. Error-free cardiac cycles are of vital importance for providing adequate diagnostic quality video in noisy channels. Moreover, instantaneous intrarefreshes [at a macroblock (MB) level for H.264/AVC and previous standards] placement can be designed to match the d-ROI. Toward this direction, redundant slices (RS) can be used to maximize the video's error resiliency by adding redundant representations in the transmitted bitstream of the clinically sensitive regions only [10], [11]. Flexible MB ordering (FMO) type 2, an error-resilience tool introduced in H.264/AVC, has been extensively used in the literature to enable variable quality slice encoding [9]–[11]. Similarly, error-concealment methods can be used during decoding and/or postprocessing to improve the quality of d-ROI [14].



(a)

(b)

36	36	36	36	36	36	36	36	36	36	36
26	26	26	26	26	26	26	26	26	26	26
26	26	26	24	24	24	24	24	24	26	26
26	26	26	24	24	24	24	24	24	26	26
36	36	36	36	36	36	36	36	36	36	36
36	36	36	36	36	36	36	36	36	36	36
36	36	36	36	36	36	36	36	36	36	36
36	36	36	36	36	36	36	36	36	36	36
36	36	36	36	36	36	26	26	26	26	26

[FIG3] The diagnostically relevant medical video communication system. d-ROI are identified using automated segmentation that outlines the slice boundaries at the MB level (MB allocation map). Variable quality slice encoding is materialized using a modified H.264/AVC FMO type 2 error-resilience tool [quantization parameter (QP) allocation map] [10], [11]. (a) Segmentation. (b) QP allocation map.

RELIABLE WIRELESS VIDEO COMMUNICATIONS

A common approach for diagnostically robust transmission is to use unequal error protection (UEP) mechanisms to more strongly protect the diagnostically important regions (see Figure 2), such as customized forward-error correction (FEC) schemes [9], [15]. Service prioritization based on QoS characteristics [medium access control (MAC) layer feature of 3.5G wireless networks] can also be used for reliable wireless video communications. It allows the network's operator to try and meet application specific requests for average bandwidth provision, tolerated latency, and, most importantly, traffic prioritization. Medical video communication systems can build on these features to provide responsive (low latency) and high diagnostic quality communications (based on high bandwidth allocation) [9], [11], [14]–[16]. Selective automatic repeat request (ARQ) and hybrid ARQ are also utilized for protecting the clinical capacity of the streamed video, provided low end-to-end delay.

Cross-layer approaches for reliable medical video communications [15]–[18] are used to adapt to the wireless channel's varying state. Such approaches utilize an a priori constructed look-up table that consists of different encoding states. By monitoring QoS characteristics of different layers, a switch to a more robust state from the look-up table is triggered. In addition to the wireless network's QoS characteristics and the channel's specification, the switch decision combines source encoding parameters, objective VQA measurements [e.g., peak signal-to-noise ratio (PSNR)] and c-VQA [mean opinion score (MOS) of clinical ratings provided by the relevant medical experts]. A weighted cost function provides the threshold values based on which a switch is made. Each state in the look-up table has to conform to the underlying medical video modality's clinical criteria.

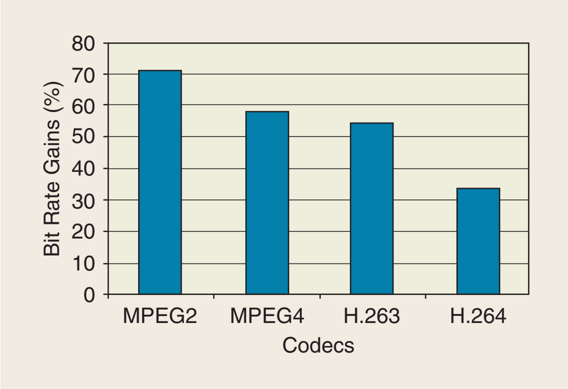
CHALLENGE: ASSESSING CLINICAL VIDEO QUALITY

Clinical validation is used to verify that the reconstructed medical video is of adequate quality. For each medical video modality, a clinically validated protocol needs to be developed that will guarantee that the used m-health system reproduces the in-hospital diagnosis [6], [8], [10]–[13], [20]. Where applicable, the diagnostically important video regions should be defined and linked to the assessment of individual clinical criteria. Clinical validation will then require medical experts to assign clinical scores to clinical criteria that are associated with the d-ROI. The latter will enable customizing objective VQA by introducing weights on d-ROI and hence increasing the likelihood of producing objective ratings that correlate with clinical ratings. Currently, objective VQA in and of itself cannot be trusted to assess the clinical capacity of the communicated videos as it may not correlate with the medical expert's ratings. Hence, there is a need to develop new, diagnostically driven quality metrics that will be ultimately used to predict clinical ratings.

Video encoding parameters can be determined based on c-VQA. Ideally, video encoding should use the same spatial resolutions and frame rates that were used during in-hospital video acquisition. When bandwidth requirements do not allow encoding at the acquired settings, c-VQA can be used to determine the minimum levels of video resolution that do not compromise the appearance of diseased regions and frame rates that do not compromise the visualization of clinical motion [10], [18], [19].

CASE STUDY

The medical video communication framework introduced in [10] is used to showcase the efficacy of diagnostically relevant design approaches. The framework uses d-ROI for efficient video encoding and VQA. For atherosclerotic plaque ultrasound videos, the diagnostically important regions are 1) the atherosclerotic plaque region, 2) the region between the



[FIG4] **HEVC bit rate gains compared to prior video coding standards.**

near and far walls, and 3) the electrocardiogram (ECG) region (where this is applicable) [see Figure 3(a)].

Clinical evaluation of the plaque region allows the medical expert to determine the plaque type and assess the plaque's morphology and motion patterns. This is the primary d-ROI, as it provides the most critical information for assessing plaque stability. A plaque rupture will lead to a stroke event. A strong predictor for stroke is the degree of stenosis, which is deducted by measuring the distance of the plaque's edge to the opposite wall. Near and far wall visualization also aid in the assessment of the plaque motion patterns. Plaques prone to rupture usually have different within plaque motions. This means that certain plaque areas have different motion patterns than the whole plaque. The ECG region, which includes the ECG waveform, helps the experts assess the plaque motion and stenosis throughout the cardiac cycle (systole, diastole, etc.).

Figure 3 shows how variable quality slice encoding is implemented using H.264/AVC FMO type 2. Initially, pixel-based segmentation algorithms identify the diagnostically important video regions, which are then used to define the slice boundaries at an MB level (16×16 pixels). Each MB is then encoded using a quantization parameter (QP) according to the slice's clinical importance. As discussed earlier, the level of compression that does not comprise the clinical capacity of individual regions is deducted using c-VQA. The proposed diagnostically relevant scheme provides for significant bit rate demands reductions without compromising clinical quality.

Still, the new HEVC standard achieves even greater bit rate gains for equivalent clinical quality. Figure 4 depicts the bit rate demands reductions achieved using a data set composed of ten atherosclerotic plaque ultrasound videos, acquired at a video resolution of 560 × 416 and 50 frames/s. The Bjøntegaard measurement method was employed to compute HEVC bit rate requirements reductions compared to prior standards using 12 different rate points (QP 20–42 for HEVC and H.264/AVC standards, and 2–31 for earlier standards), based on the experimental setup described in [6]. HEVC lowers bit rate demands approximately 33% when compared to its predecessor, H.264/AVC standard. Moreover, bit rate gains are 55% and 58% compared to H.263 and MPEG4-part 2 standards, respectively. Bit rate savings extend up to 71% for the MPEG2 standard. HEVC bit rate gains promise significant additional bandwidth to be used for maximizing video's clinical quality and robustness.

FUTURE DIRECTIONS

The wider adoption of wireless medical video communication systems relies on the development of effective methods that can match the quality of in-hospital examinations. Integration of current and emerging compression technologies and wireless networks infrastructure will allow video transmission at the acquired resolution and frame rates with the low-delay and quality requirements for emergency telemedicine. The challenge is developing the appropriate mechanisms that will guarantee that the communicated video is diagnostically acceptable. To achieve this, diagnostically driven VQA metrics need to be developed. To cater for different modality characteristics, weighted VQA scores based on d-ROI and the associated contribution to the evaluation of individual clinical criteria should be considered. Ultimately, the goal is to predict clinical quality using automated techniques, facilitated by computer aided diagnosis systems in standard clinical practice.

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(continued on page 172)

[TABLE1] OPERATIONS REQUIRED TO PERFORM THE SECTOR BINNING.

	BBA	BBP	BBR
ADD/SUB	6	$(M-3)+1$	$2(M-2)$
MUL	2	$(M-3)$	$2(M-2)$
DIV	1	0	0
ABS	3	2	0
MOV	0	$3(M-3)$	0
SHIFT	2	$(M-3)$	$2(M-2)$
BIT-ASSIGN	3	$2(M-3)+3$	$2(M-2)+2$
BIT-OP	2	$(M-3)+2$	$(M-2)+2$
OTHER	FLOOR, $\mathrm{sbc}(\cdot)$	M SIGNCOPY	$\mathrm{SBC}(\cdot)$, $2M$ SIGNCOPY

half-plane, quadrant, and octant sector calculations are used; and for both BBP and BBR, one and two multiplications in $x = x \cdot q_i$ and $x = x \times c_i$, respectively, are replaced with bit-shifting and signcopy. Finally, the loops are assumed unrolled, and therefore, no operations for iteration variable manipulation are counted.

DISCUSSION AND CONCLUSIONS

We have presented three different solutions to sector binning of a complex number or two-dimensional vector. This binning can be viewed as a quantization of the related argument. Table 1 shows the strengths and weaknesses of each solution. BBA requires division and noninteger data types, but the computational cost is independent of the number of sector bins. BBP requires the fewest number of operations for a small number of sectors, but the computational cost scales with the logarithm of N and data-dependent memory accesses are required. BBR avoids the data-dependent memory accesses at the cost of a somewhat higher number of required operations. Both BBP and BBR can be implemented with only integer data types.

Which solution to favor is a matter of the intended platform, the number of sector bins/quantization level, and the application. For embedded platforms, a moderate number of bins, and sequential processing typical for communication applications, we would generally favor BBP. However, for processing of large data chunks (e.g., images), opting for vectorization, and for platforms with readily available multipliers, we would favor BBR. Finally, for platforms with a fast division operation and in the case of a large non-power-of-two number of sector bins or floating-point data, we would favor BBA.

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