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A Survey of Cross Layer Design in Wireless Networks for Joint Optimization of Multimedia Transmission

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Abstract: Optimization of wireless network architecture plays a vital role in achieving maximum network capacity. Shared wireless media in the presence of multiple users and multiple applications need to be used optimally to enhance satisfaction of the users. Especially, mobile multimedia applications demand wireless networks to allocate resources optimally and adapt to environment dynamics. Cross Layer Design (CLD) is a paradigm to optimize traditional layers of communication network architecture. As far as video streaming is considered over wireless networks, it is challenging to achieve Quality of Experience (QoE) and Universal Multimedia Access (UMA), which addresses the problem of delivering multimedia resources under different conditions. In this paper, we focus on finding insights from the present state-of-the-art of CLD for optimization of multimedia transmission over wireless networks. It throws light into different layers and the joint optimization possibilities to leverage multimedia content dissemination in wireless networks. The insights of research findings of this paper provide valuable knowhow on joint optimization of multimedia transmission over wireless networks.

Keywords: Wireless local area network (WLAN), Wireless multimedia streaming, cross-layer design (CLD), quality of experience (QoE), universal multimedia access (UMA)

I. INTRODUCTION

Optimization of network infrastructure is a never ending process as systems are never developed, but being developed. As users share wireless medium, it is important to optimize allocation of resources. The concept of optimization can be done in multiple layers of OSI reference model [1]. Bouras et al. [2] specified that different entities are used in the cross-layer design in wireless networks for media transmission. Based on that, the optimization scheme can fall into different categories such as sender based, receiver based, network supported and hybrid approach. In the sender based approach the sender performs cross layer adaptation in terms of deployment without the need for the support from network or the receiver. In the receiver based approach, the receiver performs cross layer adaptation. Network elements are involved in the network supported cross layer optimization while the hybrid category is the combination of two or more approaches. There are different cross layer adaptation strategies such as top down, bottom up, MAC centric, application centric and integrated approaches as explored in [3]. Many researchers contributed towards the cross layer optimization.

We et al. (2005) [4] focused on the design of a cross-layered approach that could lead to solving network planning problem. This is achieved by the optimization of resource allocation procedure in the physical (PHY) and medium access control (MAC) layers. Their framework is interactive in which time sharing in MAC and operational states in PHY layers are improved interactively. Shan (2005) [5] focused on both the channel and data adaptations by proposing different cross-layer techniques that helped in adaptive video streaming. Chiang (2007) [6] focused on congestion control and power control jointly for balancing physical and transport layers in wireless multi-hop networks. Wu et al. (2007) [7] focused on video summary transmission using a novel cross-layer optimization approach in wireless networks. They used dynamic programming and lagrangian relaxation for effective video streaming. It uses source coding at the application layer, ARQ in the data link layer and adaptive modulation and coding in the PHY layer. The work is on top of the delay-distortion theoretical framework for joint optimization of layers.

Table 1: Acronyms

Acronym	Description
ARQ	Automatic Repeat Request
BER	Bit Error Rates
BS	Base Station
CLD	Cross Layer Design
CLO	Cross Layer Optimization
CPS	Common Part Sub Layer
CRL	Cross-Layer Approach Based on a Reinforcement Learning
DSC	Dynamic Service flow Change
DT	Directly Tuneable
DVB	Digital Video Broadcast
DVB-H	DVB – Handheld
ECC	Error Correction Code
HSUPA	High Speed Uplink Packet Access
IT	Indirectly Tuneable
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MOS	Mean Opinion Score
NCT	Network Coding for Throughput

NCV	Network Coding for Video
NCVD	Network Coding for Video in Depth
OBMA	Outer Boundary Matching Algorithm
OPNET	A network simulation tool that supports wireless and wired networks for empirical study.
PSNR	Peak Signal-to-Noise Ratio
QoE	Quality of Experience
QoS	Quality of Service
ROI	Region of Interest
SF	Service Flow
SNR	Signal-to-Noise Ratio
SS	Subscriber Station
SVC	Scalable Video Coding
TDMA	Time Division Multiple Access
UMA	Universal Multimedia Access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WVSN	Wireless Video Sensor Network
XLO	Cross Layer Optimizer

A cross layer approach over Wireless Video Sensor Network (WVSN) is explored in [8]. Here cross layered approach is used for energy efficiency and adaptive video compression. Xiao et al. (2011) [9] considered MPEG-4 traffic in wireless networks with cross-layer optimization using prioritized frame transmissions. They used MAC and PHY layers for joint optimization of MPEG-4 traffic. They used OPNET simulations for proof of the concept.

In this paper we reviewed many schemes that contributed towards improving QoS and QoE with respect to video streaming over wireless networks. The remainder of the paper is structured into various sections that throw light on different cross-layer design approaches for video streaming over wireless networks. It ends with conclusions and recommendations for future work.

II. APPLICATION DRIVEN CROSS-LAYER OPTIMIZATION

Khan et al. (2006) [1] proposed an application-driven framework for cross-layer optimization. This framework is meant for resource allocation to different kinds of applications in an optimized fashion in order to maximize user satisfaction and network capacity. Their optimization scheme is based on an important metric known as Mean Opinion Score (MOS). It was originally defined for assessing voice quality. According to MOS, the rating given by users is as follows.

Table 2: Showing MOS ratings

MOS Rating	Meaning
1	Bad
2	Poor
3	Fair
4	Good
5	Excellent

Khan et al. explored multi-application CLO for which they extended MOS as user-perceived quality metric used for other applications such as file download, web browsing, and video streaming. Thus it can be used across applications using the common optimization metric. The objective function is computed as follows.

$$\Phi(\tilde{X}) = \frac{1}{k}\sum_{k=1}^{k} \lambda_k \,.\, MOS_k(\tilde{X})$$

Where $F(\tilde{X})$ is the objective function in the cross layer approach. The possible parameter tuples are represented by $\tilde{\chi}$. The relative importance of the user is represented by λ_k. The decision of optimizer is computed as follows.

$$\tilde{X}_{opt} = \alpha\rho\gamma\ \mu\alpha\xi\ \Phi(\tilde{X})$$

$$\tilde{X} \in \tilde{\chi}$$

Where $\tilde{X}_{opt}$ denotes a parameter tuple meant for optimizing objective function. With the improved MOS functionality the probability is improved. The user satisfaction is mapped to corresponding MOS score as shown in the Table 3.

Table 3: Mapping user satisfaction and MOS

User Satisfaction	MOS
Very satisfied	4.4
Satisfied	4.3
Some users dissatisfied	4.0
Many users dissatisfied	3.6
Nearly all users dissatisfied	2.6
Not recommended	1.0

With respect to cross-layer optimization, they proposed cross layer design architecture. The architecture considers the parameter abstraction with respect to application, data link and physical layers. The cross layer architecture is as shown in Figure 1.

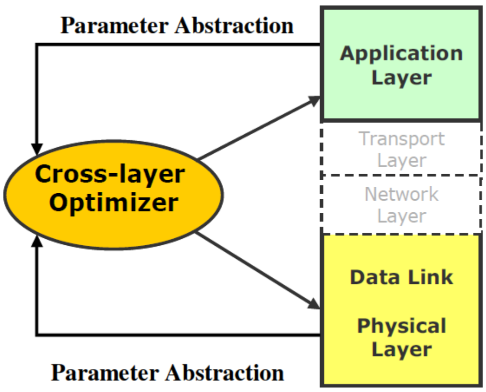

Figure 1: CLD architecture for application-driven cross-layer optimization

The cross layer optimization policy includes three types of users, namely users requesting voice service (U), users requesting file download service (V) and users opting for video conference (W). Based on the kind of application, users need different resource allocation over the wireless channel. The transmission rate depends on the share of medium access, channel code rate, and the modulation scheme. They utilized transmission policies for every service. Optimizations are made in terms of MOS maximization, and throughput optimization. Their empirical results revealed improved user perceived quality under different conditions [1].

III. CONCEALMENT TECHNIQUES FOR QUALITY OF EXPERIENCE IN VIDEO STREAMING

Concealment techniques are used in video streaming applications at the receiver end as a post process in order to conceal lost video information. Often it is required in case of wireless channels which are error prone. Debono et al. (2012) [10] considered m-Health which is a medical application in the healthcare domain for exploring CLD in order to improve QoE. The motivating scenario they considered of m-Health is shown in Figure 2. With respect to ultrasound scan video, physician decides the region of interest (ROI). He doesn't need the entire video. In such a case, it is possible to have CLD to improve that part of video streaming quality. The process concealment techniques are applied to the ROI in order to avoid computational complexity and reduce delay in video streaming. It is quite suitable in mobile healthcare services.

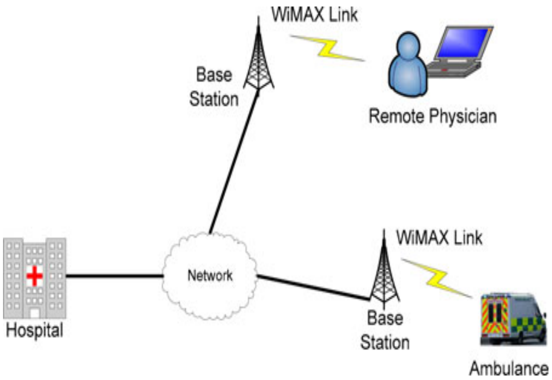

Figure 2: Motivating scenario for CLD with ROI in mobile WiMAX

The remote physician can view the ROI of video pertaining to ultrasound taken in the ambulance. Thus in the m-Health application doctor can suggest treatment immediately without waiting for the patient to come to the hospital and perform ultrasound in the hospital premises. This can improve QoE in the healthcare domain with respect to video streaming of ROI. This can also improve QoS in the domain. Error concealment applied in the process is shown in Figure 3. The cross layer QoS parameters considered are as shown in Table 4.

Table 4: QoS Parameters for CLD

Layer	Parameters
Physical	Modulation and coding
Data link	BER, SNR, CQI, ARQ, and FEC
Application	ROI, Quantization index, coding and PSNR

As said earlier, error-prone wireless channels may cause packets to be dropped by the network layer. Reconstructing such lost information is essential. Such quality is ensured by error concealment techniques. Error concealing is a post decoding process which does not increase bandwidth needs as well. Concealment can be done in both temporal and spatial domain. The process includes enhanced list of temporal motion vectors, optimal motion vector selection by using boundary distortion measurement, and refinement of the replacing macro block.

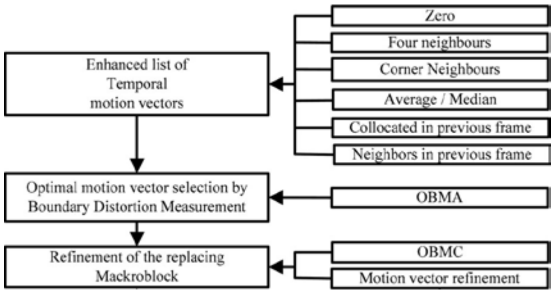

Figure 3: Error concealment in the ROI

Outer Boundary Matching Algorithm (OBMA) is used for the computing absolute difference between the external boundary of corrupted one and the 2-pixel-wide outer boundary of replacing macro block. With respect to CLD an integrated approach is followed. The CLD parameters aforementioned in the Table 2 are categorized into four groups with regard to parameters abstraction. The first group is directly tunable (DT) time slot assignment in TDMA. The second group is indirectly tunable with Bit Error Rates (BER) on coding. The third group is Signal-to-Noise Ratio (SNR) and the fourth group is channel state probabilities from which frame-loss probabilities are derived [10].

IV. JOINT OPTIMIZATION OF USER EXPERIENCE AND ENERGY EFFICIENCY FOR WIRELESS MULTIMEDIA BROADCAST

Singhal et al. (2014) [11] proposed a CLD optimization to achieve energy efficiency and QoE. They considered the number of users of the service. They grouped the number of users as part of joint optimization considering estimated channel conditions and user device capabilities. By using adaptive content delivery, they could achieve both energy efficiency and QoE. Scalable Video Coding (SVC) is used to achieve this. Along with this cooperative game and optimal source encoding are also used for the purpose. Another important concept used at the user side is layer-aware time slicing. Adaptive modulation and coding is used to ensure quality at the receiver end. Their optimization framework is as shown in Figure 4.

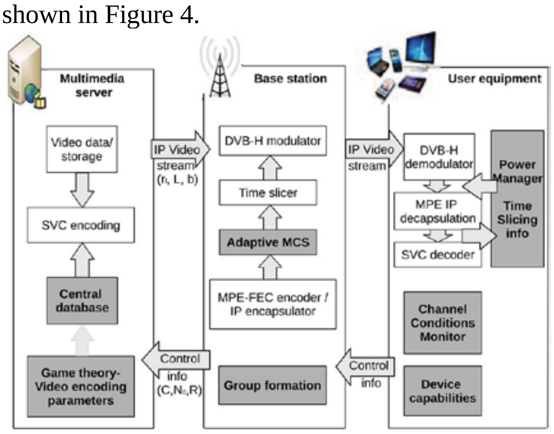

Figure 4: Overview of Digital Video Broadcast – Handheld Framework

Video data storage and SVC encoding are done at multimedia server. Modulation, time slicing, adaptive modulation and coding scheme (MCS) are done at the base station. The user equipment has demodulator, decapsulation, and the SVC decoder that perform the respective job. User equipment also includes mechanisms to monitor channel conditions and device capabilities. Game theory video encoding parameters are used in the multimedia server for dynamic control. Adaptive MCS achieved 16.6% higher capacity in serving users besides being energy efficient.

V. REINFORCEMENT LEARNING ALGORITHM WITH CROSS-LAYERED APPROACH (CRL)

Alinejad et al. (2012) [12] also used ultrasound video streaming in m-Health scenario in healthcare domains. Similar kind of work was explored in [10] where ROI was the main focus. Mobile WiMAX and High Speed Uplink Packet Access (HSUPA) networks are considered for empirical study. Figure 5 shows a motivating scenario of m-Health. The mobile video streaming in real time environment, especially in healthcare domain, can help in improving QoS. This is possible as the patient's vital signs are video streamed to remote physician in order to get timely treatment, thus saving time and effort. This can be done without geographical (relative) and time restrictions.

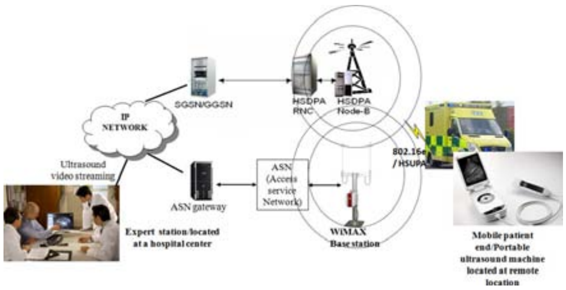

Figure 5: The mobile ultrasound video streaming in m-Health

The m-Health scenario needs untrasound video streaming over WiMAX network with good quality. Good quality is achieved here using cross-layer design. There are many cross layered approaches. They can be classified into five categories known as top down, bottom up, application centric, MAC centric and integrated approaches.

VI. DIFFERENT CLD APPROACHES

In the top down approach the upper layers like application and MAC layers take responsibility to have QoS strategy for lower layers. The optimizer shown in Figure 6 takes QoS requirements from application layer and reconfigures physical and MAC layers in order to have optimized video streaming.

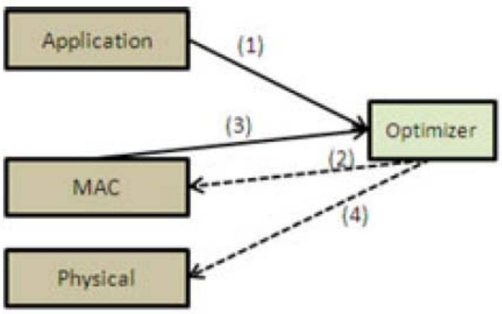

Figure 6: Top down approach

In the bottom up approach the optimizer observes service variations in lower layers and insulates upper layers from such variations. The upper layers are re-configured based on the state of lower layers in order to reduce the effect of variations of lower layers. MAC layer status influences the application layer parameters[12].

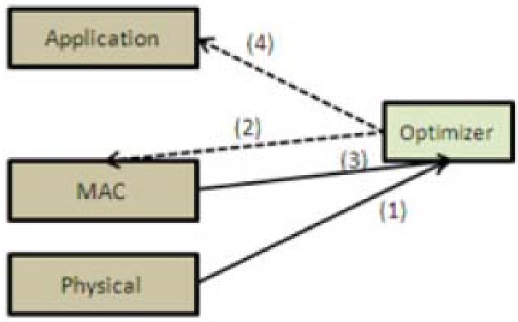

Figure 7: Bottom up approach

With respect to the application centric approach, the optimizer is location in the application layer to re-configure other layers in top-down or bottom-up fashion. The re-configuration is based on the need for the application layer. This approach cannot be considered for the real time video streaming applications due to slower rate of changes in upper layers[12].

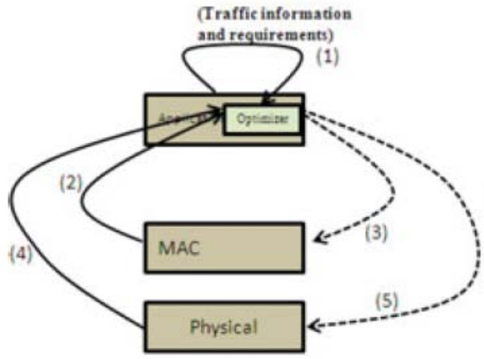

Figure 8: Application centric approach

In case of MAC-centric approach optimizer lies in the MAC layer. The optimizer takes QoS needs from the application layer. Then MAC layer optimizes its own parameters followed by that of physical layer based on the observations in the physical layer. When compared to the application-centric approach, this model has faster reaction time[12].

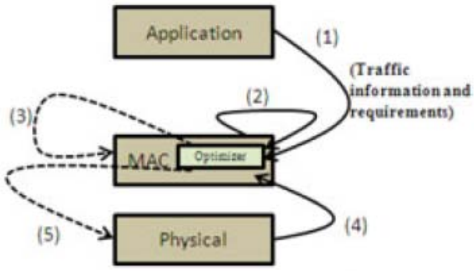

Figure 9: MAC centric approach

The last approach is known as an integrated approach. As shown in Figure 10, this model takes information from application layer, MAC layer and Physical layer in order to make optimization decisions. As all the layers are considered for optimization, this approach is suitable for improving QoS with respect to video streaming in m-Health[12].

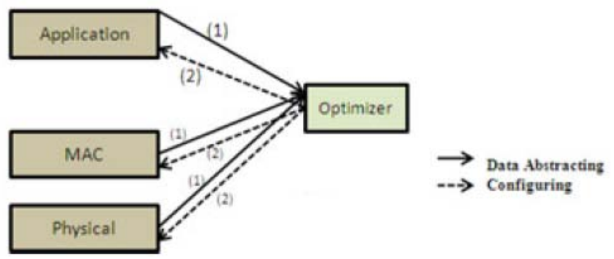

Figure 10: The integrated approach

As discussed, different approaches have different mechanisms. In [12] the integrated approach is used for improving video streaming in healthcare domain. They used an algorithm known as cross-layer approach based reinforcement learning (CRL) algorithm which is implemented using the cross-layer design approach presented in Figure 11.

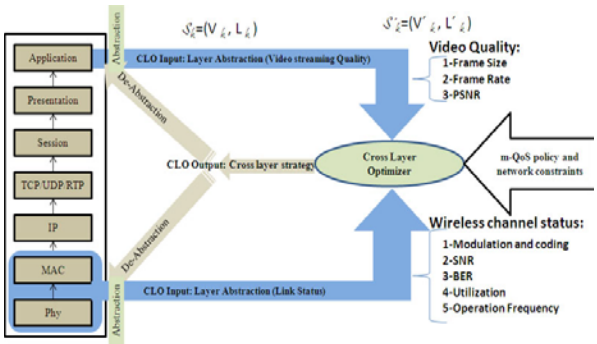

Figure 11: CLD with Application, MAC and PHY layers

The cross-layer optimizer receives quality requirements from application layer. The QoS requirements provided by the application layer include frame size, frame rate and PSNR. The MAC and the PHY layers considered to improve different parameters such as modulation, coding, SNR, BER, utilization and operation frequency. The cross layer optimizer also considered QoS policy and network constraints in order to provide the best approach in optimization. The optimizations are reflected back into the application layer, the MAC and PHY layers for enhanced quality of ultrasound video streaming over the m-Health network in healthcare domain[12].

VII. OPPORTUNISTIC NETWORK CODING FOR VIDEO STREAMING

As rendering high quality videos over wireless channels is a challenging problem, network coding is the mechanism to improve QoS in video streaming. This approach is explored by Seferoglu and Markopoulou (2002) [13]. Their main focus was to mix packets from different flows into a single packet using network coding technique. This could improve throughput and information content besides enhancing video quality. They considered different types of packets in the process of optimization. The packets are known as primary packet, side packet, active packet and inactive packet. Primary packet is the packet chosen from Tax queue for network coding. The side packet is the packet in Tax queue, which is other than the primary packet. The active packet is the packet in Tax queue which can be considered as primary. The inactive packet is the packet in Tax queue that cannot be chosen as the primary packet.

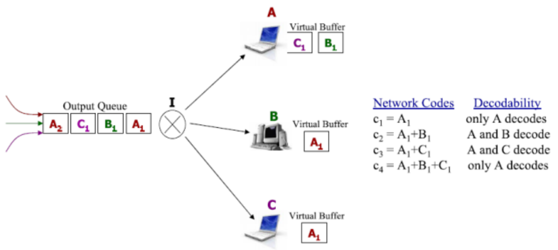

Figure 12: The mechanism of NCV

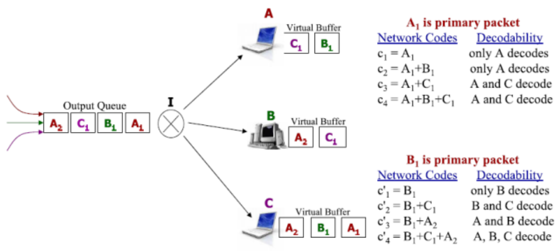

Figure 13: The mechanism of MCVD

Two network coding algorithms are proposed. They are known as NCV and NCVD. NCV selects the best network code among different coding opportunities for best video streaming quality. On the other hand, NCVD considers the entire queue and improves possibilities of candidate primary packets for increasing possibilities in network coding. Thus NCVD performs better than NCV. The mechanics of the two algorithms are presented in Figure 12 and Figure 13.

VIII. CROSS-LAYER OPTIMIZATION IN WIMAX NETWORKS

Abdallah et al. (2010) [14] proposed an architecture for cross layer optimizer (XLO). They used the QualNet simulator for implementation of their architecture. Video adaptability and enhanced admission control function are used to achieve optimization. They considered traffic between subscriber station (SS) and base station (BS). Actual optimization is performed using two layers in the network, namely application and MAC layers. The optimization between MAC and application layers is shown in their work for enhanced video streaming. Figure 14 shows the overview of the optimization.

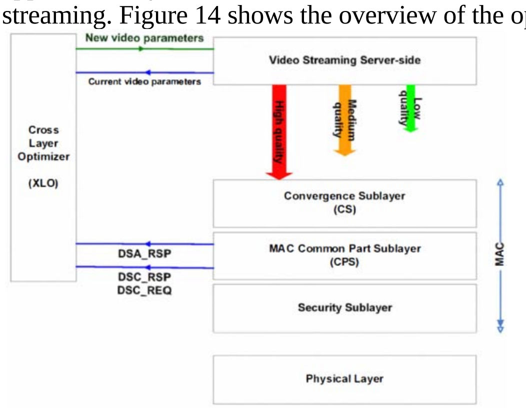

Figure 14: Overview of XLO

The XLO is able to obtain current and new video parameters from the application layer at server side. Then the MAC layer is optimized in order to enhance video streaming quality. Dynamic Service flow Change (DSC) is computed in the optimizer and the results are sent to MAC Common Part Sub Layer (CPS), which renders core MAC functionality in terms of the connection establishment, bandwidth allocation and system access. It is also responsible for managing service flow (SF).

IX. APPLICATION – CENTRIC CLD

Khan et al. (2016) [15] proposed a cross-layer optimization strategy for enhanced video streaming over wireless networks. Their strategy uses three layers for adaptation as shown in Figure 15. They also studied performance gain and tradeoffs between that and computational cost and communication cost. They did the optimization in three steps. In the first step they followed the layer abstraction where layer specific parameters are obtained. Then optimization was done based on the parameters of layers considered for objective function in order to improve the user-perceived quality of video streaming. They classified the parameters into directly tunable, indirectly tunable, descriptive and abstracted.

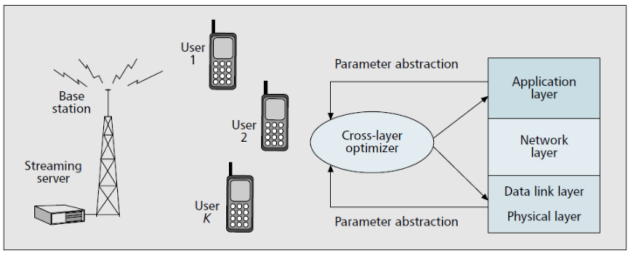

Figure 15: Overview of application centric CLD

The application scenario is shown on left side while the CLD approach is shown in the right side. The layers used for optimization are application layer, data link layer and physical layer. In the application layer video source rate is considered for optimization. In the same fashion, time slot allocation is considered from data link layer and modulation scheme is considered from physical layer to enhance perceived video quality. At radio link layer, four parameters are used for optimization. They are channel coherence time, data packet size, transmission packet error rate, and transmission data rate. PSNR at the receive end is used to measure the user-perceived video quality.

Summary

Table 5: Summary of CLD approaches reviewed

Author & Year	Technique	Advantages	Disadvantages	Remarks
Seferoglu and Markopoulou (2002) [13]	Opportunistic Network coding	Improving quality video streaming over wireless networks	Needs to be improved with hybrid data flows.	Network throughput and video quality are evaluated.
Bouras et al. (2004) [2]	Inter-layer optimization techniques	Layer wise parameters presented for CLD.	-	Cross layer approaches like sender based, receiver based, network supported, and hybrid are discussed.
Wu et al. (2005) [4]	Iterative cross layer optimization	Improved data transmission rate.	Distributed approach is not used for analysis.	PHY and MAC layers are used for optimization.
Shan (2005) [5]	CLD for adaptive real time streaming	Bandwidth efficiency and low delay	Fine Grain Scalable (FGS) features can be adapted.	Priority based ARQ and scheduling algorithms are used
Khan et al. (2006) [1]	Scheme based on Mean Opinion Score (MOS)	User perceived quality improvement	-	Application layer performance metric MOS is used.
Khan et al. (2006) [15]	Application driven CLD	Video streaming performance is improved.	Trade-off is there between performance gain and computational cost.	Application layer, data link layer and physical layers are used for optimization
Wu et al. (2007) [7]	Joint optimization of Modulation and coding, allowable retransmission, and source coding.	Delay performance and distortion gain performance improved.	Only single user and single transmit and single-receive antenna model is explored.	Video summary transmission is given importance in the research.
Chiang (2007) [6]	Optimization decomposition with congestion control and power control	Energy efficiency and increased end-to-end throughput.	-	Balancing transport and physical layers
Abdallah et al. (2010) [14]	Cross layer optimizer (XLO)	Better quality video streaming in WIMAX networks	Multi-hop relay is not considered in optimization.	MAC and application layers are used for optimization
Xiao et al. (2011) [9]	CLD for MPEG-4 with prioritized frame transmissions	IEEE 802.11e WLAN capabilities improved.	-	OPNET is used for empirical study.
Debono et al. (2012) [10]	CLD with concealment techniques	36 dB PSNR is achieved for video quality in optimized region of interest	Error control is still to be explored to reduce areas needing concealment.	Healthcare domain is used for empirical study
Alinejad et al. (2012) [12]	CLD with real time rate adaptation of ultrasound video streaming	Improved performance in mobile WiMAX	Did not focus on video coding issues.	Experiments are in healthcare domain

Singhal et al. (2014) [11]	User grouping and Scalable Video Coding (SVC)	Improvement in QoE levels of all users	-	Inspired by innovative cooperative game.
Alaoui-Fdili et al. (2015) [8]	Energy and Queue Buffer Size Aware MMSPEED-based protocol	Energy efficiency and QoS besides 33% life time extension.	-	CLD for video delivery over WVSNs

As shown in Table 5, different research contributions on CLD are summarized in terms of techniques employed, advantages and disadvantages.

X. CONCLUSIONS AND FUTURE WORK

In this paper we made a survey of important CLD approaches found in the literature. Most of the CLD approaches used application layer, physical layer, MAC layer and data link layers. Different categories of CLD approaches are found. They include top-down approach, bottom-up approach, MAC centric approach, application centric approach and integrated approach. They are known as CLD adaptation approaches. In the same fashion, an optimization scheme can fall into different categories such as the sender based, the receiver based, the network supported and hybrid approach. The researchers contributed towards CLD using their simulation work using NS2, OPNET and QualNet. Video streaming problems in different scenarios were explored. For instance, m-Health is the healthcare scenario where the quality of ultrasound scan is important for the remote physician to provide timely instructions and treatment to a patient who is located in some other place and needs treatment in real time. Many such utilities were found in the literature. This paper focused on some of the important approaches and their merits and demerits in solving the problem of achieving QoE and QoS in video streaming over wireless networks. This research can be extended further by proposing a new CLD scheme that can maximize QoE and QoS in wireless networks.

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