Adaptive Cross Layer Approach for Video Transmission Over Cognitive UWB Network

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***Abstract*— The demand of quality of service (QoS) for multimedia transmission over wireless network raises huge challenges such as time-varying channel conditions, limited resources, tight delay constraints, high bandwidth demand and complex protocol design. Therefore, there is need to efficiently utilize and manage the interactions among different layers of the protocol stack using cross layer design (CLD) approach in order to provide necessary support for video applications. This paper presents our proposed strategies for adaptive video transmission over Cognitive Ultra Wideband (C-UWB) network using MAC centric CLD approach. Generally, the proposed MAC centric CLD framework consists of sensing module, adaptive resource allocation module and adaptive quantization scale module. Two techniques are proposed namely; Basic CLD (B_CLD) and Enhanced CLD (E_CLD). In the B_CLD, the decision strategies to stream video packets over C-UWB network are based on the pre-determined thresholds. On the other hence, decision strategies in E_CLD are based on Lagrange optimization, which is implemented in the packet reception rate (PRR) based resource allocation scheme and adaptive quantization scale. Simulation results showed that the proposed E_CLD scheme has significantly improved the video quality when compared to the Basic CLD scheme and the non-CLD scheme.**

Keywords-cross-layer design; cognitive UWB network; video transmission

I. INTRODUCTION

One of the major driving forces of a new technology is a combination of man's endless thirst for knowledge, unequal intuitive mind and limitless ambition to better his life. This is translated into an increasing demand for a low cost, higher speed and bandwidth hungry applications that run on many consumer electronic devices with seamless connectivity. However, the business models in emerging wireless systems are bounded with a concept of proportional end-user's cost to the volume of data transmitted but with limited bandwidth resources and transmission power. Due to this, industry players, scientists and academicians are urged to venture a new paradigm in offering the technical solutions. Cognitive radio (CR) is one of innovative solutions to address the issue of congested but inefficient spectrum utilization, introduced by Mitola [1].

In cognitive radio networks, it is the responsibility of cognitive users (CUs) to ensure that its existence will not cause any harmful interference to the primary user (PU). When the wireless systems that are potential candidates for cognitive radio are considered, Ultra Wideband (UWB) seems to be one of the tempting choices [2]. It is due to its potential to fulfill some of the key cognitive radio requirements such as causing no interference to PUs, bandwidth, transmit power, supporting various throughputs and providing adaptive multiple access. In underlay mode, C-UWB user is allowed to co-exist in the same spectral and temporal domains with the PU by lowering the amount of transmit power. This is done by following the FCC rules [3], which authorized the use of UWB spectrum with spectral mask of -41.3dBm/MHz.Additionally, UWB is also known as a popular candidate for high rate data transmission over wireless personal area network.

Specifically on multimedia transmission over cognitive UWB (C-UWB) network, the key challenges come from the nature of multimedia application and cognitive radio itself as follows [1]:

a) Resource constraint such as spectrum bandwidth, transmit power, data rate and time slot access.
   - In Time Division Multiple Access (TDMA) based MAC protocol, the main concerning issue is the sharing of time slots among wireless users. While in cognitive radio, data transmission and sensing activity are usually carried out separately at different time. Thus, appropriate time slots allocation and optimal scheduling are very important to guarantee accurate sensing information without causing any unintended delay.

b) Dynamic network condition over time due to interference, shadowing and multipath fading.
   - During good channel condition, it is better to transmit data with higher rate to increase the throughput. However, it may cause higher bit error rate. Therefore, an optimal approach between the two conflicting objectives need to be addressed carefully.

c) Heterogeneous video traffic
   - Due to frame dependency, loss of certain important frame will lead to indirect loss of other frames and may caused higher distortion impact. Hence, each video frame should be treated differently according to their frame priority, dependency and size.

d) Stringent delay constraint
   - Delays of less than 200 milliseconds are required for interactive applications, such as videoconferencing, surveillance etc., while for multimedia streaming applications delays of 1-5s are tolerable. Packets that are arrived after their display time are discarded at the receiver side.

In cognitive networks, there is need for greater interaction among different layers of the protocol stack in order to achieve the end-to-end goals and performance in terms of resource management, security, QoS or other network goals. Therefore, cross layer design approach is needed. Cross layer design approaches can be categorized into application adaptation, application-centric adaptation, middle layer centric approach, middleware-based adaptation, and autonomous adaptation [8]. In this paper, we proposed a MAC centric cross layer design that is aware of MPEG-4 QoS requirements and PHY channel conditions to address the issue of multimedia transmission over C-UWB network. It is called a MAC centric CLD because the optimization and decisions are carried out by the MAC layer.

The rest of this paper is organized as follows. Section II presents the design concept of our proposed CLD which involve PHY, MAC and APP layer. In Section III, detail of the CLD functional components namely; video traffic module, adaptive resource allocation module, adaptive Q-scale module and sensing module are elaborated. Results and analysis are given in Section IV. Finally, conclusion and future recommendations are drawn in Section V.

II. THE PROPOSED CROSS LAYER DESIGN CONCEPT

CLD plays a vital role at the design stage of CR system. The general key idea in CLD is to select the appropriate parameters which can be manipulated to gain a dramatic positive impact. Fig. 1 shows the layers involved, the parameters used and the adaptation actions performed in the proposed CLD design. The design goals are quantified in terms of PSNR, job failure rate (JFR) and user's perspective view. PSNR serves as an objective measure of the reconstructed video with respect to the uncompressed video frame. While JFR is defined as a ratio of total number of frames that are failed to be transmitted and total frames transmitted.

At the bottom, PHY layer is responsible in sensing the UWB wireless channel condition. Since sensing and data transmission are done separately at different time, optimal sensing period should be allocated at the MAC in order to obtain accurate sensing information while at the same time avoiding intolerance additional delay for video packet transmission. SNR of data packet is chosen as a link quality indicator, so as to detect spectrum availability. Practically, SNR is more reliable parameter because it is obtained after completion of demodulation process at the receiver [2]. The sensed information is then shared with the MAC and APP layer for optimal cross layer strategies.

At the APP layer, MPEG-4 video is encoded with different quantization scale during pre-process. The goal of pre-process video encoding is to prepare the video for adaptive quantization (Q) scale and hence allow rate adaptation during network simulation. The Q-scale is optimally adapted in accordance to the channel conditions. Detail of the Q-scale adaptation is elaborated in Section III-D. Heterogeneous video traffic is considered with attributes that are represented in terms of frame dependency, frame type, frame size and delivery deadline. At the MAC, optimal resource allocation is performed in accordance to UWB wireless channel conditions, QoS target set by the APP layer and queue status.

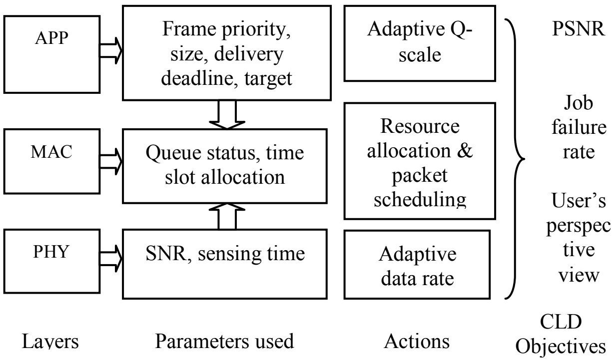

Figure 1. Layers involved, parameters used and action required in the proposed CLD

The optimal decisions are then forwarded to the respective layers for actions. At the APP layer, the Q-level is adjusted at every start of the GOP structure to maintain the synchronization and refresh of motion prediction algorithm. Due to adaptive Q-scale at the APP layer, the data rate at the PHY layer is also adaptive. Conversely, MAC layer schedules the sensing and data transmission in accordance to the varying channel conditions and the target packet reception rate (PRR). This will effectively reduce the unnecessary resource consumption and hence improve the system performance. Video frames are then scheduled for transmission in accordance to their attributes. The CLD design is simplified with no routing protocol and UDP is adopted at the transport protocol. This assumption is valid because UWB is targeted for WPAN with coverage within 10m and thus no hopping is required.

Centralized topology is adopted with one of the C-UWB nodes acts as a central controller surrounded uniformly by several others C-UWB nodes. The central controller is assigned as a common receiver while the other C-UWB nodes are assigned as transmitters with MPEG-4 video application.

III. CLD FUNCTIONAL COMPONENTS

The proposed functional components of the CLD for multimedia transmission over cognitive UWB consists of video traffic module, resource allocation module, scheduler module, sensing module and adaptive Q-scale module. These components perform the actual cross layering task to support efficient wireless video transmission over cognitive UWB network. The state machine diagram and the algorithm are as shown in Figs. 2 and 3 respectively.

Initially, the target packet reception rate (PRR), optimal sensing time and delivery deadline are pre-determined for each C-UWB node. We assumed that the central controller knows the target QoS in advance. Referring to Fig. 2, the MAC centric CLD manager receives all required parameters from the CLD functional modules that involve APP, MAC and PHY layer for necessary parameter optimization. Once the optimized parameters are determined, it will be sent back to the respective layers for further actions.

At every video frame, C-UWB users trigger the central controller about its intention to perform local sensing. The C-UWB users report their sensing information to the central controller to be fused for the final decision of PU presence. The time of packet delivery is checked with the delay deadline to determine whether the packets in queue are expired or not. If expired, the packets are discarded from transmission. The Q-scale adaptation is carried out at the start of every GOP structure marked by the I-frame. Optimal resource allocation is performed based on the parameters passed from the APP and PHY layer. The optimized timeslot allocation, Q-scale and average of sensed SNR are then updated and passed back to the APP and MAC layer for packet transmission.

The MAC protocol is basically motivated from IEEE802.15.3 [10]. Each super frame starts with a beacon period (BP), during which the central controller sends the beacon containing network synchronization and control message. Then, C-UWB nodes can access the channel using contention-free with mechanisms that is based on slotted TDMA. However, the proposed MAC CLD eliminates the need of dedicated channel time slot request from each C-UWB nodes to the central controller and hence reduced the delay.

A. Sensing Module

The sensing module is responsible in monitoring the SNR level of each cognitive UWB users in the network. The SNR is represented by;

$$SNR = \frac{P_{ti} L_{ij}}{\eta B} \tag{1}$$

Where P_{ti} is average transmit power of node i, L_{ij} is signal power attenuation, η is background noise energy and B is bandwidth. To calculate the signal power attenuation, UWB Tarokh's propagation model [7] is adopted as follows:

$$L_{ij} = [L_0 + 10\alpha \log_{10}(\frac{d_{ij}}{d_0})] + S; \quad d_{ij} > d_0 \tag{2}$$

where L_0 is path loss at reference distance, α is path loss exponent, S is shadowing, d_0 is a reference distance and d_{ij} is the distance between the $user_i$ and $user_j$. From (2), the bit error rate (BER) and energy per bit can be calculated directly.

Local sensing is performed by each cognitive UWB user, while the central controller fuses the overall SNR information for cooperative sensing decision. In a cooperative spectrum sensing system using OR-Rule, the PU is considered to be present if any of the CU detects the presence of the PU. Assuming that there are N identical and independent cognitive radios in the cooperative spectrum sensing system, the cooperative probability of detection Q_d and probability of false alarm Q_f using OR-rule data fusion are given by:

$$Q_d = 1 - \prod_{i=1}^{N}(1 - P_{d,i}) \tag{3}$$

$$Q_f = 1 - \prod_{i=1}^{N}(1 - P_{f,i}) \tag{4}$$

where P_d and P_f are the probability of detection and probability of false alarm of a stand-alone cognitive radio respectively. To ensure almost accurate information of the instantaneous channel conditions, local sensing is triggered at every video frame interval. Assuming a worst case scenario for C-UWB, our previous findings in [11,12] proposed 14µsec as the optimal sensing time for multimedia transmission over cognitive UWB. The results proved that only minimal overhead is introduced from sensing activity and the impact to video transmission is also minimal.

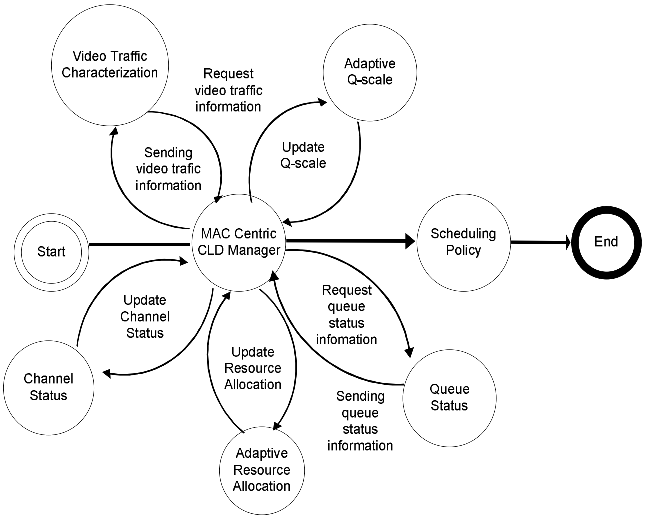

Figure 2. State machine diagram of the proposed CLD

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ALGORITHM: Wireless video transmission basic-CLD

INITIALIZATION:

// To determine the frame type (I, P, B), size and dependency
Video traffic characterization ( );
SET target PRR;   // The set target QoS for video application
SET delivery deadline;
SET optimal sensing time;
REPEAT

FOR every video frame DO
//check delay delivery constraint

IF (T_delivery < T_deadline) THEN
Sensing ( ); // to obtain channel condition status
          IF (video frame is I-frame)
                    Q-scale adaptation ( ); // Q-scale is changed at the start of new GOP
          ELSE
                    // Q-scale unchanged
          END IF
Queue ( ); // to obtain queue status
Resource allocation ( ); //to determine time slot allocations
END IF
END FOR
Update number of time slots allocation
Update average sensed information
    Update Q-scale
    n = n + 1; // Update iteration
UNTIL n = max_n; // repeats algorithm until the last video frame
```

Figure 3. The proposed CLD algorithm

B. Heterogeneous Video Traffic Module

The role of video traffic module is to identify and classify the MPEG-4 video traffic in terms of frame type, frame size, dependency, delivery deadline and distortion impact. Delivery deadline, T_deadline is defined as the time by which the data units (DUs) must be decoded to be useful. It corresponds to the decoder timestamp in MPEG terminology. Each DU represents one of the I,P or B frames. Distortion impact is defined as the amount by which the distortion at receiver decreases if the DU is decoded on time at the receiver. Each DU_j has a distortion impact, Δd_j which is assumed to be constant for all the GOPs. The overall distortion can be computed as the initial distortion, d_0 (ie: the distortion when no DUs are decoded) minus the sum of decrease Δd over all the DUs that have been decoded on time. Both sensing and video traffic module are responsible in providing appropriate sensing information and traffic classification to the MAC layer.

C. Adaptive Resource Allocation Module

Since the network traffic is bursty, a fixed assignment of time or frequency slots to users is proven inefficient. In a case of basic CLD, linear adaptive resource allocation is adopted. In this case, the instantaneous SNR, SNR_i is compared with the two thresholds; SNR_{low} and SNR_{high}. SNR_{low} is obtained when the BER target of 10^{-4} is achieved, while SNR_{high} is determined when the BER target of 10^{-6} is achieved. Details on how the SNR threshold is determined can be found in [11]. Based on the works, SNR_{low} is set to -3dB while SNR_{high} is set to -1dB. When the channel condition falls within this allowable operating region, the time slots are assigned as follows;

$$M_i = 70 * SNR_i + 210 \tag{5}$$

M_i is the allocated time slots for user i. The equation above is derived from linear correlation between SNR value and the allocated time slot.

Linear adaptive resource allocation is then further improved in the enhanced CLD scheme by also considering the instantaneous SNR and packet reception rate (PRR) of other cognitive users in the network. We named the technique as PRR based resource allocation and details of the algorithm can be found in [13-14]. To ensure efficient resource distribution among users, queue status is also considered before the actual time slot, M_{i_actual} is assigned. Assuming the number of packets in queue is $N_{\_queue}$ and L_{min} is the minimum data packet length allowed, the actual time slot assignment for PRR based resource allocation algorithm is as shown in Figure 4. Following the conditions, wastage of resources are reduced efficiently.

D. Adaptive Quantization Scale Module

Distortion of the decoded video may originates from the quantization incurred at the decoder. In order to maintain the target BER for multimedia application, we proposed to adjust the Q-level in accordance to UWB wireless channel condition. The change in source rate may result in the fluctuation of the encoded video quality. To overcome this problem, source coding rate is only adjusted at the start of each GOP. It is known that larger step size (higher Q-scale) results in a lower bit rate and larger amount of distortion. Hence, the optimal Q is also related to a well known rate-distortion (R-D) optimization problem; minimize distortion D, subject to a constraint R_c on the number of bits used, R. The constrained problem is as follows:

$$\text{Min } \{D\} \text{ subject to } R < R_c \tag{6}$$

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//Calculate the initial resource using PRR based resource allocation
$M_i = \frac{K}{1 + \sum_{j=0}^{j=M} \frac{(1 - PRR_{i})}{(1 - PER_{j,j\neq i})}}$
//Check the queue status for actual resource allocation
    IF ($N_{\_queue} = 0$)
        $M_{i\_actual} = L_{\_min}$
    ELSE IF ($M_i < N_{\_queue}$*210µsec)
        $M_{i\_actual} = M_i$
    ELSE IF ($M_i \geq N_{\_queue}$*210µsec)
    $M_{i\_actual} = N_{\_queue}$*210µsec
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Figure 4. Algorithm for the proposed adaptive resource allocation module

The above optimization problem can be elegantly solved using Lagrangian optimization and becomes;

$$\text{Min } \{ J \}, \text{ where } J = D + \lambda R \tag{7}$$

where the Lagrangian R-D functional J is minimized for a particular value of the Lagrange multiplier, λ. Previous study had shown that [15];

$$\lambda = 0.85\,(Q)^2 \tag{8}$$

At sufficiently high rates, the distortion impact can be approximated as;

$$D \cong (2Q)^2/12 \tag{9}$$

In the basic CLD scheme, the optimal Q-value is obtained through exhaustive search. While in Enhanced CLD scheme, the optimal Q-value is obtained by adopting the leaky bucket concept. For both schemes, the optimal λ is calculated using equation (8) in order to evaluate its impact to distortion.

IV. SIMULATION PARAMETER

Simulations were divided into 3 stages namely; pre-process, network simulation and post-process. During pre-process, video samples are pre-encoded. The pre-process is performed only once and the generated trace files can be used over and over by new network simulations. While network simulations were carried out using NS-2. The post process is mainly deal with decoding the compressed video, calculating the performances and displaying the decoded received video. Tables 1, 2 and 3 show the parameter settings used. The target PRR and BER are set to 92% and 10^{-6} respectively to meet the QoS requirement of multimedia application.

TABLE 1. MPEG-4 ENCODER SETTING

Parameter (unit)	**Settings**
Video input	Akiyo, Foremen, Coastguard
Group of Picture	12
Frame rate (frame/sec)	30
Frame deadline (sec)	1/30
Frame size (width x height)	176 x 144

Quantization scale	2-31
Number of frames	423

TABLE 2. MAC LAYER SETTING

Parameter (unit)	Settings
Super frame size (µsec)	1-65536 (adaptive)
Packet size (byte)	2000
PHY header time (µsec)	15
MAC header (byte)	16
Header check sequence, HCS (byte)	2
Frame check sequence, FCS (byte)	4
Short inter frame space, SIFS (µsec)	10
IP/UDP/RTP header (byte)	48
Acknowledgement	Immediate
Retransmission	3

TABLE 3: NETWORK SETTING

Parameter (unit)	Settings
Path loss exponent (dB)	1.7
Shadowing (dB)	2.8
Path loss at reference distance (dB)	50.5
Modulation	QPSK
Channel bandwidth (MHz)	528
Data rate	100Mbps

V. RESULT & ANALYSIS

Table 4 summarizes the highest PSNR obtained at different UWB channel conditions and its corresponding optimal Q-value obtained through heuristic approach. As expected, the optimal Q-value moves towards higher value when channel condition becomes worse. Conversely, the Q-value is small when the channel condition is good. Meaning, smaller Q-value is chosen to reduce source coding distortion. When the assigned Q-value is higher than the optimal Q-value, the source distortion will increase (due to lower source rate). On the other hand, if the assigned Q-value is smaller than the optimal Q-value, more packets are generated per video frame and thus would lead to higher JFR. These explain why degradation in PSNR performance happened when non-optimal Q-value is used.

Akiyo, Foreman and Coastguard video sequences are used in the simulations to represent low, medium and high motion video respectively. In the non-CLD scheme, each user is assigned with fixed amount of time slot all the time regardless of their instantaneous channel conditions and the QoS. Alternatively, Basic CLD scheme adopted the linear resource allocation with Q-value adaptation. The video quality is further improved in the E_CLD scheme by utilizing Lagrange optimization in the PRR based resource allocation and Q-scale adaptation. Table 5 shows the performance in terms of average PSNR over the whole video frames. It is evident that the proposed Basic CLD and E_CLD scheme are more beneficial to high motion video (Coastguard) than the low motion video. Close observation of the PSNR value at each video frame shows that the proposed Basic CLD and E-CLD scheme give significant performance enhancement during bad and medium channel conditions. This really gives an advantage to cognitive UWB network, which is targeted for low SNR region to coexist with the PU. However, during good channel conditions, it is observed that the non-CLD scheme outperformed the proposed CLD schemes. E_CLD also outperformed Basic CLD scheme in terms of the average JFR. While the JFR for non-CLD scheme is the worst.

The performance can be much more appreciated if observed from the user perspective view as illustrated in Figs. 5, 6 and 7 below. However, due to page limitation, we present the video quality improvement difference between the non-CLD scheme and Basic CLD scheme. The figures obviously demonstrate that the received video quality is almost undecipherable when subjected to the non-CLD scheme during bad channel condition.

TABLE 4: OPTIMAL QP FOR VARIOUS CHANNEL CONDITIONS

Distance (m)	Average SINR (dB)	Optimal QP	Optimal PSNR (dB)
1	15.280	2	42.32
2	10.143	2	42.32
3	7.169	2	42.32
4	5.026	2	42.32
5	3.398	2	42.32
6	2.034	2	42.32
7	0.912	2	42.32
8	-0.090	2	42.32
9	-0.900	5	32.76
10	-1.737	13	24.92
11	-2.420	10	24.27
12	-3.080	15	22.57
13	-3.660	15	20.62

TABLE 5: AVERAGE PSNR FOR VARIOUS VIDEO SAMPLES

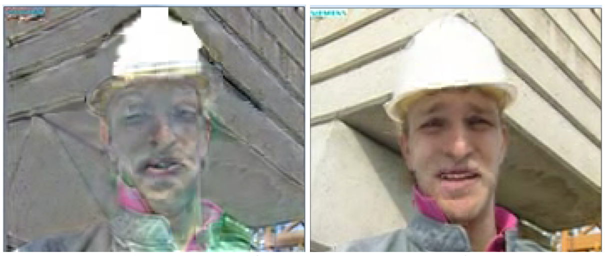
Video Sequence	Non-CLD [dB]	Basic CLD [dB]	E_CLD [dB]
Akiyo	28.68	29.08	30.21
Foreman	15.21	16.68	18.06
Coastguard	13.66	17.02	18.31

TABLE 6: AVERAGE JFR FOR VARIOUS VIDEO SAMPLES

Video Sequence	Non-CLD (%)	Basic CLD (%)	E_CLD (%)
Akiyo	3.5	1.0	0
Foreman	4.7	2.2	1.1
Coastguard	6.9	2.6	0.8

(a) No CLD, frame 59, PSNR= 12.76dB
(b) Basic CLD, frame 59, PSNR= 28.52dB

Figure 5. Subjective evaluation of the low motion video (Akiyo)



(a) No CLD, frame 64, PSNR= 12.78dB
(b) Basic CLD, frame 64, PSNR= 18.19dB

Figure 6. Subjective evaluation of the medium motion video (Foreman)

(a) No CLD, frame 25, PSNR= 14.5dB
(b) Basic CLD, frame 25, PSNR= 21.37dB

Figure 7. Subjective evaluation of the high motion video (Coastguard)

V. CONCLUSION

This paper highlighted our proposed Basic CLD scheme and E-CLD scheme that is aware of the varying channel conditions and the target QoS at the APP layer in allocating sufficient time slots and in choosing the optimal quantization scale. We conclude that SNR is the main parameter to be considered in the CLD approach. Changing SNR channel conditions lead to different optimal Q-value. The proposed MAC centric CLDs had proven to be successfully improved the received video quality when. We believed that the CLD design can be further improved if more intelligent packet scheduling is adopted. Additionally, other optimization methods such as particle swamp optimization shall be considered to speed up the computation time for optimization and hence further reduce the end to end delay.

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