Adaptive Bitrate Video Transmission Over Cognitive Radio Networks Using Cross Layer Routing Approach

Amjad Ali, Sikandar Tariq, Muddesar Iqbal*, Li Feng, Imran Raza, Muhammad Hameed Siddiqi, and Ali Kashif Bashir

***Abstract*—** Due to the recent developments in the wireless mesh and ad-hoc networks, multi-hop cognitive radio networks (MCRNs) have attained the significant attention towards providing the reliable multimedia communications. However, in reliable multimedia communications each multimedia application observed a very stringent quality-of-service (QoS) requirements. Moreover, in MCRNs, channel allocated to the multimedia secondary users (MSUs) can be re-occupied by the primary users (PUs) at any time which causes the end-to-end- path discontinuity that severely affect the performance of the MCRNs. Therefore, under the dynamic channel availability, selecting an end-to-end path that is not only stable but also fulfills the QoS requirements of the real time and multimedia (RM) applications is a challenging task and still an open research problem. Hence, in this paper, we propose a cross-layer routing scheme that supports adaptive bit-rate multimedia (ABM) transmissions over MCRNs. Moreover, our path selection is based on the QoS-aware end-to-end path delay, and PU-activity aware end-to-end path stability metrices. Furthermore, to avoid the PU interference, continuity in transmission, efficient channel utilization, and supporting error resilience over time varying wireless channels our selected end-to-end path is periodically updated. Simulation study shows that the proposed scheme is more robust and suitable for supporting ABM over MCRNs.

Index Terms- Cross layer routing, Adaptive Bit-rate Multimedia, QoS, Reliable communications.

I. Introduction

Since past two decades, severe spectrum underutilization is reported and according to the statistics about 15%-80% of the wireless spectrum is being wasted around the globe [1-2]. The major reasons of this huge wastage of the scare spectrum resource are the fixed spectrum allocation policies and the centralized management.

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Thus, in order to improve the spectrum utilization and to accommodate the emerging applications over a limited wireless spectrum, the federal communication commission (FCC) approved a law, in which the secondary users (SUs) can exploit the licensed spectrum opportunistically without interfering the primary users (PUs) [3]. Hence, the term cognitive radio (CR) was introduced by Joseph Mitola III with the sole purpose to improve the spectrum utilization.

Recently, there has been a great demand for the bandwidth hungry, real time and multimedia (RM) applications [4]. Such demand is promoted by the two factors; 1) rapid deployment of the multi-hop wireless technology to support pervasive connectivity, and 2) the pervasive use of computing devices (i.e., computers, laptops, automotive computing devices, personal digital assistants, wearable devices, and smart phones, etc.) [5]. Furthermore, the RM applications observed a very stringent quality-of-service (QoS) requirements in terms of the bandwidth, delay, packet loss ratio, and reliability etc. However, the bandwidth is one of the major issues in the traditional multi-hop mesh and ad hoc networks but the prologue of the CR, especially multi-hop CR technology has significantly resolved this issue [6-7]. Therefore, recently multi-hop CRNs (MCRNs) are gaining more attention toward supporting the new RM applications. In the MCRNs, a multimedia SU (MSU) is more concern about the QoS level observed rather than the way a particular service is provided. Therefore, if the RM applications QoS requirements are not considered carefully while establishing an end-to-end routing path, the reduction in QoS at the receiver MSU may impede the success of the CR technology.

In the MCRNs, channel allocated to the MSU can be re-occupied by the PUs at any time which causes the path breakage or transmission discontinuity that may severely affect the performance of the MCRNs. Therefore, under the dynamic availability of wireless spectrum, selecting an end-to-end path that is not only stable but also fulfills the QoS requirements of the RM applications is a challenging task and still an open research problem [8]. Moreover, the MCRNs are heterogeneous networks in nature, in which different available channels can provide different QoS levels which make the aforementioned problem more complex. However, the traditional routing techniques meant for wireless mesh networks (WMNs) or mobile ad-hoc networks (MANETs) based on the conventional routing metrics (i.e., minimum average packet loss rate

(MAPLR), minimum hop count (MHC), and minimum average packet delay (MAPD) etc.) are failed to provide the desired QoS in the MCRNs under the PU interference, dynamic availability of wireless channels, and time varying channel conditions [9]. For example, the MAPD-based routing is ineffective in the MCRNs because the selected routing-path with the minimum average delay does not necessarily means that it fulfills the others desired QoS requirements, and the selected path is stable in terms of the PU interference. Similarly, the MHC-based routing scheme that chooses a best end-to-end path based on the MHC, ignores the others important QoS parameters, such as buffering delays at intermediate nodes, the packet loss ratio (PLR) over the selected end-to-end path, supported bitrate, and the most important factor of the dynamic channel availability due to PUs interference over the selected end-to-end path. The MAPLR-based routing only considers the minimum average packet loss rate while ignores the other important QoS requirements as well as it does not consider the PUs interference. Thus, ordinary routing protocols do not fully consider the RM transmission QoS requirements as well as it is not suitable for CRNs under the dynamic availability of wireless channels. Thus, our main contributions are listed as below:

1. We proposed a cross-layer routing scheme that supports adaptive bit-rate multimedia (ABM) transmissions over the MCRNs.
2. We also introduced two new routing metrics; 1) QoS-aware end-to-end path delay, and 2) PU-activity aware end-to-end path stability. Thus, in our proposed scheme, the end-to-end path selection and channel allocation is based on these two parameters.
3. We jointly considered the end-to-end path selection and the channel allocation to maximize the perceived video quality at the receiver MSU.
4. We proposed a dynamic path updation scheme to ensure the transmission continuity and efficient channel utilization.
5. The performance of the proposed scheme is measured in terms of the channel rank, end-to-end path stability time, end-to-end path delay, end-to-end packet loss ratio, throughput, peak signal-to-noise ratio, and no. of times end-to-end path breaks due to PU interference and compared the performance with the traditional non QoS-based routing scheme.

Our remaining paper is organized as follows. We presented the state-of-the-art in Section II. Section III presents our system model and assumptions. PU activity-aware channel indexing along with others routing metrices calculations are presented in Section IV. Proposed cross-layer routing scheme along with the periodic updation scheme is discussed in Section V. The simulation results and discussion are provided in Section VI. Finally, the paper's conclusion is presented in Section VII.

II. Related Work

In this section, we present the state-of-the-art on the reliable and multimedia communications over CRNs. Maximum literature available is focused towards addressing the physical layer and non-real time data transmissions issues. However, some researchers investigated the real time and multimedia transmissions issues for CRNs with multiple aims and objectives which is presented below.

P. Wang et al. in [10] used a TDMA-based medium access scheme for enabling voice service over CRNs. The authors characterized a single WLAN under one channel that is accessed among multiple PUs and SUs in a time slotted fashion. In order to facilitate the SUs to exchange the information among the nodes, a priority-based virtual queuing interface scheme is proposed in [11]. This interface further provides the dynamic strategy learning to enable the MSU to selects the multiple frequency channels for communication. A digital fountain codes-based scheme is proposed in [12] to distribute the multimedia contents over unused channels and acts as erasure-correcting codes to combat packet loss due to channel conditions or PU interference. In this scheme, the channels are selected to establish a link for multimedia user based on its quality that is measured in term of PU interference. A two-tier spectrum allocation method to allocate the spectrum to SUs based on their QoS requirements is proposed in [13], in which channels are indexed according to QoS requirements of MSUs. A real time distributed multi-agent learning-based cross layer scheme is proposed in [14] to dynamically exploit available channels. This approach uses the existing interference information to attain the learning efficiency. Explicit model-based and model-free approaches are used to obtain the performance of real-time multimedia services. In [15], a QoS-based cross layer architecture is proposed for 3G, WiMAX, and WiFi access technologies under CRN environment. Based on the QoS requirements of application the best access technology is selected for the MSU. In [16], a cross layer scheme is proposed for enabling multimedia traffic over CRNs. This scheme jointly optimizes the refreshing rate and application layer parameters with spectrum access and sensing methods. Refreshing rate is adopted according to channel sensing information's. In [17], a quality-driven cross layer architecture is proposed to optimize the QoS parameters residing in the entire network protocol stack. The authors used MIN-MAX dynamic programming to jointly optimize the cognitive MAC scheduling, encoder behavior, transmission, modulation, and coding under distortion-delay framework.

In [37-38], Ali et al. introduced a channel clustering scheme for MCRNs. In the proposed scheme the authors quantified the PU licensed channels into multiple clusters according to the supported bitrate, packet delay variation, and packet delivery ratio to facilitate the MSU for

Table 1: Notations.

$\sigma(t, t+\tau)$	Source traffic measured in bits generated during the time interval $[t, t+\tau)$
F_j	Total number of incomming flows at any intermediate node j
B	Buffer size of a queue
$Q_j(t)$	Queue size at time t over node j
$C_i(\tau)$	Channel i instantaneous capacity at time t
$S_i(\tau)$	Channel i service provided measured in bits, during time interval [0,t)
I	Number of available channels at time t
M_j	Number of tuned/used channels at node j
CC	Control channel
ε	Monitoring error
$Min\ TOL_t^i$	Minimum transmission opportunity length over channel i at time t
$Max\ TOL_t^i$	Maximum transmission opportunity length over channel i at time t
$Q_j(t)$	Queue size of node j at time t
$\sigma(t, t+\tau)$	Amount of source traffic generated during $[t, t+\tau)$
j_l	Number of intermediate nodes between any pair of source and destination (S_l,D_l) where $l = (1,2,3 \dots)$

transmitting multimedia transmission over cellular or one-hop CRNs. Similarly, in [39], the authors proposed a RaptorQ-based efficient multimedia transmission scheme for underlay cellular CRN. In the proposed scheme, available time over licensed channel is divided into various portions to improve and assist the relayed communication. In order to facilitate the priority-based communication in IoT-based CRN, a priority-based channel assignment scheme is proposed in [40]. In the proposed scheme, the higher priority users are given more and reliable channel at top priority while the least or lower priority users are given less reliable or a smaller number of channels. An extended cognitive mobile terminal scheme known as "ExCogNet-MT" is introduce in [41]. In the proposed scheme the receiver estimates the channel quality measured in term of signal to noise ratio (SNR). Further, bit error rate and SNR on the communication channel is measured by comparing the standard deviation of the received signal strength and processed signal strength. In [18] a cross layer routing and spectrum access framework known as routing and dynamic spectrum allocation (ROSA) is proposed for mobile ad hoc CRNs (MACRNs). the ROSA maximizes the throughput of the SU by performing joint routing, dynamic spectrum allocation, scheduling, and transmit power control but it does not deal with the multimedia and real time transmission. Joint stable routing and channel assignment (J-SRCA) protocol is proposed in [19] for MACRNs. The J-SRCA elevates the network throughput based on the mobility prediction. Similar to ROSA, the J-SRCA also do not consider the RM transmissions. Sample division

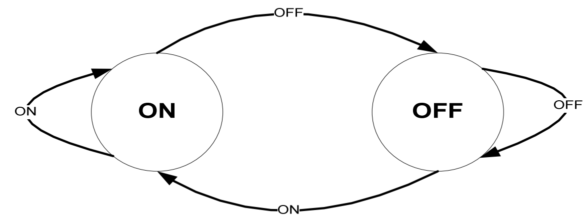


Fig. 1: Markov model for PU activities monitoring.

multiplexing (SDM) based multi-path routing for multimedia traffic is proposed in [20]. Single traffic stream is divided into multiple streams with minimum traffic demand supported by channels and then multiple paths for each traffic stream are found using Max-flow algorithm. Joint multipath routing and channel allocation scheme for CR enabled wireless mesh network is proposed in [21]. It supports multi-source video-on-demand (VoD) applications.

The above techniques discussed in [11-13] are intended for single-hop as well as are not cross-layer. The techniques discussed in [14-17] are intended for single-hop SU using cross layer architecture. However, the methods discussed in [20, 21] are silent about PU interference that is main characteristic of CRNs. Moreover, multiple paths can induce packet reordering problem that severely affect the performance of CRNs and furthermore for each frame finding desired number of paths every time is not guaranteed CRN which further make their proposed schemes more complex. We propose a cross layer QoS-based routing approach for supporting ABM transmissions over MCRNs, in which the end-to-end path selection is based on the PU activity-aware channel indexing and queuing delay estimation-based on effective capacity theory. Moreover, to avoid the PU interference, path, channel utilization, and to support the error resilience under time varying wireless channels we proposed periodic path updation scheme.

III. System Model

In the following subsections, we discuss our system models and assumptions.

A. Assumptions

First, each MSU is equipped with M frequency-agile half-duplex CRs following the suggestion in [22]. One radio is dedicated for sensing and detecting the availability of wireless channels and the same radio is also responsible to share the control messages (including routing messages) this radio is called monitoring radio (MR). Remaining radios would be utilized for sending and receiving multimedia traffic data. Control and routing messages are exchanged through control channel (CC), similar to [23]. PUs activities (ONN/OFF) on licensed channels are following the exponential arrival model, similar to [24]. Last, PU activity detection on the licensed channels is trustful, so we are not considering sensing error.

B. *Network Architecture*

We consider MCRN environment with no central administrator node for controlling the network wide communication. The PUs behaves in purely random and unpredictable fashion, making spectrum opportunities for MSUs highly unpredictable and the MSUs are not aware of the PUs traffic pattern/type over their licensed channels. There are total N MSU in the network. Each MSU is aware of QoS requirement of its multimedia traffic that is given in form of end-to-end delay. Total I heterogeneous licensed channels are available in the network. Every MSU individually detect the licensed channels; therefore, the availability of channels to each MSU is different and depends on its vicinity and PU interference. M CRs are available to each MSU; each radio can be tuned to only one channel to communicate with one-hop MSU. The proposed protocol is on demand routing protocol. The MSU who wants to exchange multimedia traffic initiate route request message, which piggybacks its multimedia traffic requirements and its spectrum information.

IV. Metrics Calculation for Cross-Layer Routing

In this section, we discuss the calculations of our all routing metrics.

A. *PU Activity-Aware Channel Indexing*

PUs behaves in unpredictable or purely random fashion, makes channel opportunities for the MSU highly unpredictable or random [25]. As PUs are paid users and have exclusive rights to use licensed channels. Therefore, their transmissions would should interfered by the MSU. Therefore, the MSU need to sense the wireless channel first and detect its availability before exploiting it [26]. Thus, PUs activities need to be accurately modeled so that the MSU can evacuate the licensed channels without affecting PUs activities. For efficient and reliable transmissions, the MSU need to identify the transmission opportunities lengths. Thus, the precise estimation of the PU activities can lead to enable QoS-based multimedia applications over MCRNs and make much more effective licensed spectrum usage for MSU.

B. *PU-Activities Monitoring and Channels Indexing*

In the section, we discuss PU activities monitoring procedure proposed in our preliminary work [42]. The PU arrivals and utilization time on each channel is exponentially distributed.

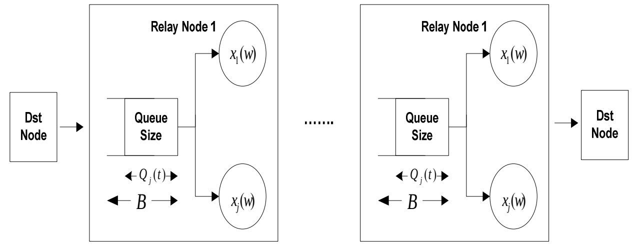


Fig. 2: Queuing model

Channels are continuously monitored through the MR in a round robin fashion using two state Markov model shown in Fig.1. The MR monitors each channel for a very short time interval say ΔT. During monitoring, if monitored channel is found in ON state, the MR marks it busy and on its next monitoring turn if the MR found it in ON state then the MR found no arrival in the monitored interval. Hence the time period $t_2 - t_1$ will be noted as *utilization time*. But if monitored channel is found in OFF state at time t_2 , then the time $t_2 - (t_1 + \varepsilon)$ will be noted as *utilization time* with monitoring error ε . Where t_1 and t_2 represent last and current time. Similarly, if the MR found monitored channel in OFF state at time t_1 and then at time t_2 it found the same monitored channel in OFF state, the time $t_2 - t_1$ will be noted as *free time*. But if monitored channel is found in ON state at time t_2 , then the time $t_2 - (t_1 + \varepsilon)$ will be noted as *free time* with monitoring error ε.

C. *Expected $Min\,TOL$, $Max\,TOL$, and Channel Rank Calculation*

Expected minmum and maximum transmission opportunities lengths have a significient impact in enabling the RM transmission over MCRNs. The estimation procedure from monitoring collected information (MCI). The rank of channel i is calculated on the basics of the MCI. High value of the rank represents stable or good channel while low value represents unstable or bad channel. We are talking about stability or un-stability in context of PU interference and TOLs. The detail discussions on how to calculate the expected minmum and maximum transmission opportunities lengths and ranked are given in [42].

D. *End-to-end Path Stability Time Metric Calculation*

End-to-end path stability time (EPST) represents the period of time before the selected end-to-end path get failed by PU interference or in other words it represents the time period of selected channels over all links of end-to-end path before they get affected by PUs interference. It is one of routing metric we use to select end-to-end path for transmitting RM transmission over MCRNs. Assume there are h_p hops/links in the end-to-end path p at time t, then the path stability time is presented as

$$EPST_{\mathrm{p}}(\mathrm{t}) = \frac{1}{\sum_{k=1}^{h_p} \frac{1}{Min\,TOL_t^{i,k}}} \quad (1)$$

Eq. (1) shows that the $EPST_{\mathrm{p}}$ is decided based on the all links stable times together which is based on the minimum transmission opportunity length of link/hop k using channel i at time t represented as $Min\,TOL_t^{i,k}$. It also shows that decreasing the end-to-end path length or improving the link's stable times can increase $EPST_{\mathrm{p}}$.

E. Delay Analysis

In the MCRNs each node contains multiple heterogeneous channels those offer different service rates. Each intermediate CR node act as relay node to forward the other's traffic. Hence, resources (i.e., queue buffer etc.) on each CR node is shared among many traffic flows. This may lead different end-to-end delay on different paths. Furthermore, delay is a key performance metric in enabling the RM transmission on the MCRNs. Therefore, we compute hop-to-hop delay using following two parameters:

1. Queuing delay
2. Service delay

Queuing delay is measured in terms of time that a particular flow's wait in queue before its turn comes. Service delay is also measured as the total time required to transmit the intended flow data, which depends on the channel service rate and amount of data. In our paper, we considered that each intermediate relay node only maintains a single buffer to store all incoming traffic flows as shown in Fig.2. We analyze the delay on each CR node using effective capacity (EC) theory, which is widely used to analyze the MAC layer performance in wireless networks [27][28]. We used deterministic linear bounded arrival process (LBAP) which is also known as leaky-bucket constraint traffic model [29][30] to model incoming traffic at cognitive node. This model is based on two parameters; 1) bucket size ∂, and 2) token generating rate α. The upper bound of the source traffic over any time interval τ is given as below:

$$\sigma(t, t+\tau) \leq \alpha\tau + \partial \quad (2)$$

Where $\sigma(t, t+\tau)$ is the amount of source traffic generated during $[t, t+\tau)$ and $\{\sigma(t), t \geq 0\}$ is the arrival process which in our case is possion arrival process with $\sigma(t)$ is amount of data in bits. Let $\sigma(t, t+\tau) = \sigma(t+\tau) - \sigma(t)$ is the cummulative arrivals over time timerval $[t, t+\tau)$ for any $t+\tau \geq t \geq 0$.

Let B be the total buffer capacity/length and $Q_j(t)$ is the queue size at time t on node j. $C_i(\tau)$ is instantaneous capacity of channel i at time t. We assume all nodes have the same buffer length B while queue size $Q(t)_j$ may vary due to amount of incoming traffic data and service rate provided by the tuned channels at node j. We will compute the effective bandwidth functions (EBFs) for packet service, channel sevice, and packet arrival processes.

Table 2: Spectrum parameters [34].

Channel No	Bit rate (Kpbs)	Packet loss ratio
1	4000	5%
2	5000	5%
3	4500	5%
4	2000	1%
5	96	1%
6	1000	1%

Firstly, we derive EBF for packet service process of any node j. let b_i is the bandwidth in Hz , and SNR_i is the signal to noise ratio (SNR) in dB of channel i. Hence, the instantaneous capacity $C_i(t)$ measured in bps of channel i at time t is given below according to channon theorm [31].

$$C_i(t) = B_i Log_2(1 + SNR_i) \quad (3)$$

Thus, the totall serving capacity of node j at time t is cummulative capacity of all the tuned channels, given as follow.

$$SC_j(t) = \sum_{m=1}^{M} C_m(t) \quad (4)$$

Where M is the number of assigned channels at node j. Here we only consider the channels those are assigned on radio interfaces and operating simultaneously. Thus, total service provided in bits by node j is given in equation (5).

$$S_j(t) = \int_0^t SC_j(t)dt \quad (5)$$

Secondly, we compute EBF or effective capacity function of packet service process for node j, The Gartner-Ellis limit $\psi_i(-w)$ of the packet service process of node j is given as follow.

$$\psi_j(-w) = \lim_{t\to x} \frac{1}{t} log\ E\left[e^{-wS_j(t)}\right] \quad (6)$$

Then the EBF for the packet service process of node j is defined as follow.

$$\gamma_j(w) = \frac{-\psi_j(-w)}{w} \qquad \forall\, w > 0 \quad (7)$$

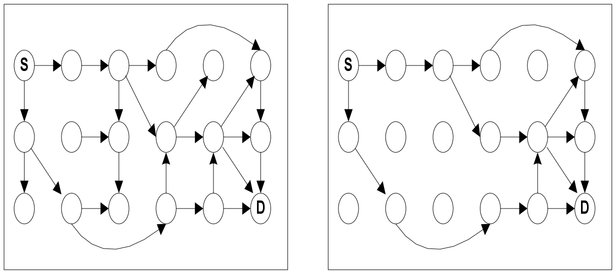
That is,

$$\gamma_j(w) = -\lim_{t\to x} \frac{1}{wt} log\ E\left[e^{-w\int_0^t SC_j(t)dt}\right] \quad (8)$$
$$\forall\, w > 0$$

Where x is the amount of time and its value is based on the real-time multimedia service type. The EBF of packet sevice process $\gamma_j(w)$ of node j captures the stochastic properties, for instance when $w \to 0$, it converge to the average service rate while $w \to \infty$, it converges to the minimum service rate [27]. Similarly, we can derive the EBF of any single channel i given as follow.

$$\rho_i(-w) = \lim_{t\to x} \frac{1}{t} log\ E\left[e^{-w\int_0^t C_i(t)dt}\right] \quad (9)$$

Then the EBF of the packet service process of channel i is as follow.



(a) RREQ Path Discovery. (b) Available Paths.

Fig. 3: Path Discovery.

$$\chi_i(w) = \frac{-\rho_i(-w)}{w} \qquad \forall\, w > 0 \qquad (10)$$

That is,

$$\chi_i(w) = -\lim_{t\to x}\frac{1}{wt}\log E\left[e^{-w\int_0^t C_i(t)dt}\right] \qquad \forall\, w > 0 \qquad (11)$$

Finaly, we compute the EBF of packet arrival process at node j. we assume possion arrival process with arrival rate λ. Let $\lambda_j(t)$ is the cummulative arrival process during time interval $[t, t+\tau)$.

$$\lambda_j(t) = \sum_{s=1}^{F_j}\sigma^s(t, t+\tau) \qquad (12)$$

The EBF of the packet arrival process $\eta_j(w)$ is as follow.

$$\Omega_j(-w) = \lim_{t\to x}\frac{1}{t}\log E\left[e^{-w\lambda_j(t)}\right] \qquad (13)$$

$$\eta_j(w) = \frac{\Omega_j(-w)}{w} \qquad \forall\, w > 0 \qquad (14)$$

Thus, the derivation for the possion arrival process with arrival rate λ is as follow.

$$\eta_j(w) = \frac{\lambda(e^w - 1)}{w} \qquad (15)$$

The queuing process $\{Q_j(t)\}$ evolve according to following recursion [28].

$$Q_j(0) = 0\,, Q_j(t+1) = \max\{\,0, Q_j(t) + \lambda_j(t) - \varphi_j(w)\} \qquad (16)$$
$$t \geq 0$$

Thus, the queuing length $Q_j(t)$ at node j is difference of total serving capacity and total packets arrived in time interval [0,t) ,which is computed as follow.

$$Q_j(t) = \left(\lambda_j(t) - \varphi_j(w)\right) \qquad (17)$$

Let $T_j^{F_s}(t)$ be the waiting time for intended traffic flow F_s where $F_s = \sigma_s(t)$ in the queue of relay node j during time interval for [0,t) is given below.

$$T_j^{F_s}(t) = \frac{1}{Q_j(t) * \gamma_j(w)} \qquad (18)$$

$ST_i^{F_s}(t)$ is service delay over channel i for flow F_s

$$ST_i^{F_s}(t) = \frac{1}{\sigma_s(t) * \chi_i(w)} \qquad (19)$$

Ch Id	Ch Rank	Min TOL (second)	Bit Rate (Kbps)	PLR
3	80	2.47	4500	3%
2	30	1.5	5000	2%
5	15	0.5	96	1%
4	10	0.35	2000	3%
1	5	0.25	4000	4%

(a) CI table format.

Node Id	Value
1	3
2	3
3	2
4	0
5	1

(b) ACL Format.

Fig. 4: Node tables.

F. End-to-end Path Delay Metric Calculation

End-to-end path delay (EPD) represents the amount of delay over any path between source and destination. The EPD is our second path selection metric to enable the RM transmission over the MCRNs. The EDP of any path is computed based on queuing delay at relay nodes, and service delay on available channel. Firstly, amount of delay $D_i^j(t)$ occurred from one relay node to other for some traffic flow F_s at time t using channel i is computed as follow. We derived $D_i^j(t)$ from airtime link cost [32].

$$D_i^j(t) = \left[(T_j^{Fs}(t) + ST_i^{F_s}(t)) + \frac{F_s}{C_i(t)}\right] \times \frac{1}{1-e_i^{fr}} \qquad (20)$$

Where $T_j^{Fs}(t)$ is the amount of time that flow F_s wait in queue of relay node j as given in equation (18)? F_s is the amount of traffic data and $C_i(t)$ is the capacity of channel i. Thus, the ratio $\frac{F_s}{C_i(t)}$ provides the service delay by using channel i. e_i^{fr} is the frame error rate over channel i and the ratio $\frac{1}{1-e_i^{fr}}$ gives the amount of time required for successfully transmitting a frame from relay node j to its next node $j+1$. Let's assume that there are total N_p number of channel switches along the end-to-end path p that is h_p hops long and D_{sw} is the switching time caused by the MSU switches between two different channels. The D_{sw} may vary from 150 μs to 200 μs for real devices [33]. Thus, end-to-end switching delay for path p at time t is computed as given below:

$$D_p^{sw}(t) = N_p \times D_{sw} \qquad (21)$$

Finally, end-to-end delay $EDP_p(t)$over path p of h_p hop length at time t is calculated as follow:

$$EDP_p(t) = D_p^{sw}(t) + \sum_{j=1}^{h_p} D_i^j(t) \qquad (22)$$

G. End-to-end Loss and Available Bit rate Metric Calculation

Every cognitive node measures the bit rate and packet loss ratio (PLR) over available channels. Table 2 [34] is a snapshot of available channels, their respective data rate and PLR on CR node j . Every CR appends bitrate and PLR

Algorithm 1: Adjacent Channel List Updation

Inputs: $Set\ of\ CNs$
Output: *One-Hop ACL*
Begin
```
1:  for each cn ∈ CN do
2:      for each one-hop_neighbor ∈ cn do
3:          Broadcast QUERY (cn) over CCC
4:          Collect the RESPONSE (one-hop_ neighbor)
5:          Update ACL_cn
6:      end for
7:  end for
```

values with route request message (RREQ) and finally at destination node PLR and bitrate of end-to-end path at time t is computed as follow:

$$PLR_p(t) = 1 - \prod_{j=1}^{h_p}(1 - PLR_i^j) \qquad (23)$$

Where $PLR_p(t)$ is end-to-end PLR of path p at time t and h_p is path length measured in term of number of hops between source and destination nodes.

$$A_p^{br}(t) = Min\left(BR_j^i, BR_{j+1}^i, \dots \dots, BR_h^i\right) \qquad (24)$$

Where $A_p^{br}(t)$ is available bitrate on path p at time t and BR_j^i is the bitrate of channel i on node j at time t. In this paper we use term bitrate and date rate interchangeably

V. Proposed Cross -Layer Routing and Channel Assignment Scheme

In this section, we propose a distributed heuristic protocol to find a joint on-demand cross layer routing and channel assignment for a RM session request that satisfying the end-to-end delay, loss, and bitrate constraints. The end-to-end path is only valid for $\boldsymbol{EPST_{\mathrm{p}}}$ period and then finally, we propose a periodic path updation mechanism.

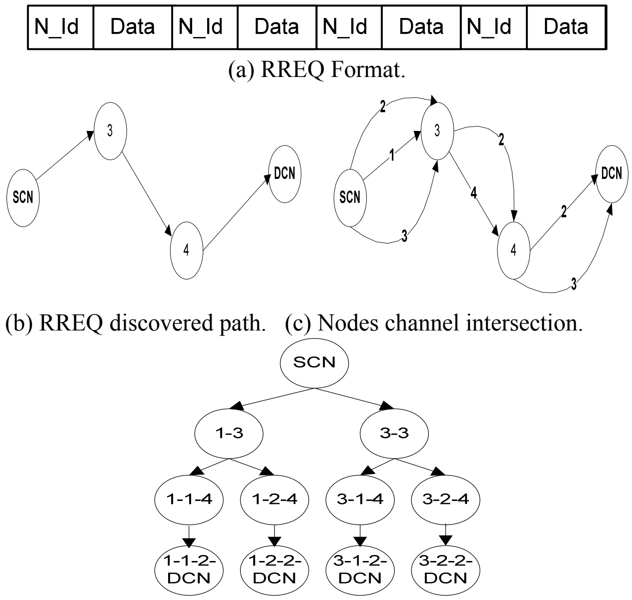
A. Path Discovery

When a source cognitive node (*SCN*) want to communication with destination cognitive node (*DCN*) for which it has no routing information, the *SCN* generates new route request (*RREQ*) message with new *RREQ-ID* and append its *Id*, channel information (*CI*) table and the RM requirements. Moreover, it is useless to send *RREQ* message toward a neighboring node having no common channel for data communication. We ensure this constraint by sending *RREQ* message to only those one-hop neighbors with whom it shares at least one common channel for data communication. Every node use CCC to broadcast *RREQ* message. When an intermediate relay node (IRN) receives RREQ it's appended its Id, CI table and queue waiting time info ($\boldsymbol{T_j^{F_s}(t)}$) and broadcast to its one-hop neighbors with whom it shares atleast one data

Algorithm 2: RREQ Initiation & Propagation

Inputs: SCN, DCN RM_{req}, Set of *IRNs*, and CI Table
Output: *RREQ Propagation*
Begin
```
if (SCN does not find a valid route to DCN from cache
   or EPST_t^p expires ) then
    SCN creates RREQ packet with new RREQ_ID
    Append Id, RM_req, and CI Table to RREQ packet
    for all 1-hop_neighbors ∈ SCN whose ACL_value
        >0 do
        Broadcast RREQ on CCC
    end for
end if
for each irn ∈ IRN do
    if (receive RREQ packet) then
        if (received RREQ from previous link or RREQ
            Hop-count ≥ previously processed RREQ
            with same RREQ_ID) then
            Discard RREQ Packet
        end if
        else
            Compute T_irn^Fs(t) according to Eq. (18)
            Append Id, T_irn^Fs(t), and CI Table with RREQ
            for all 1-hop_neighbors ∈ irn with ACL_value
                >0 do
                Broadcast RREQ on CCC
            end for
        end else
    end if
end for
```

channel. The IRN discards RREQ packet if it receives from previous processed link or if hop_count is larger than previously processed RREQ_ID. This procedure continues till the DCN receives RREQ. The DCN wait for $\boldsymbol{Max_{RREQ}}$ time and then construct all available paths. After path selection the DCN generates route reply (RREP) message and unicast it. In the RREP selected IRNs are being informed by their selected channels and time duration ($\boldsymbol{EPST_{\mathrm{p}}}$). After the expiry of $\boldsymbol{EPST_{\mathrm{p}}}$, selected path is no more valid and all IRNs release their bounded resources. To explore the available common channels for data communication each node executes Algorithm 1 periodically and updates its adjacent channel list (ACL). The format of CI table and ACL is shown in figure 4a-b. In Algorithm 1 from line 1-5 each CN broadcast QUERRY message on CCC with its Id to all of its one-hop neighbors to update its ACL. This procedure is also depicted in Fig. 3. All neighbor nodes those receive QUERRY message will reply with RESPONSE message to source node along with their Ids and ACL. Thus, finally source node maintains its ACL with its entire one-hop neighbors. This information is further exploited in propagating RREQ.



(a) RREQ Format.

(b) RREQ discovered path. (c) Nodes channel intersection.

(d) Path-channel logical tree.

Fig. 5: Logical path-channel formation.

B. Logical Paths Channel Formation

The DCN wait for Max_{RREQ} time and then based on received RREQ packets from different paths, it first constructs all available paths. Each path is composed on a set of IRNs, selected channel over each IRN, $EPST_{\mathrm{p}}$, EDP_p, PLR_p, and A_p^{br} values. Finally, the DCN selects the best path that fulfills the QoS requirements of MSU application and supports longer $\mathrm{EPST_p}$ period.

The format of RREQ packet, RREQ discovered path, node channel intersection, and path-channel logical tree formation is shown in Fig. 5a-d. The detail of logical paths channel formation process and QoS parameters computation depicted in Algorithm 2. The pseudo code from line 1-8 describes the action of expanding the RREQ packet and computing logical path based on intersection of common data channels. Paths are being computed using depth first search algorithm [35]. Line 9-18 presents the procedure for computing the QoS parameters corresponding to each path. The $\mathrm{j_p}$ is the $\mathrm{j^{th}}$ IRN on path p, $\mathrm{h_p}$ is the length of the path and $\mathrm{CS_{threshold}}$ is the channel selection threshold based on channel rank value.

C. QoS- based Disjoint Paths Selection

In multi-path, two types of disjoint paths exist [36], the link-disjoint path that contain no common link and node-disjoint path that contain no common node except the source and the destination nodes. For transmitting RM data over MCRNs, we select two link-disjoint paths; 1) primary path, and 2) secondary path. Secondary or backup path will be used if PU's occur on primary path within the valid $\mathrm{EPST_p}$ interval. In order to select link-disjoint paths we define a link divergence degree (LDG)-based parameter, similar parameter is proposed in [23]. Logical paths-channel formation and QoS-based parameters computation procedure is presented in Algorithm3.

Algorithm 3: Logical Paths-Channel Formation and QoS-Parameters Computation

Inputs: $set\ of\ RREQ\ packets\ (RREQ_{total}), SCN$
Output: Set of available paths with their *QoS Parameters*

Begin
1: **Initialize** $EPST_{\mathrm{p}} \leftarrow 0,\ EDP_p \leftarrow 0, PLR_p \leftarrow 0, A_p^{br} \leftarrow 0,$ $h_p \leftarrow 0, i_p^j \leftarrow 0,\ Paths \leftarrow \{\}, ChIn_j \leftarrow \{\}, N_p \leftarrow 0$
2: **for** each $rreq\ \in RREQ_{total}$ **do**
2: $h_p\ \leftarrow\ Hop\_count_{rreq}$
3: **for** each $j \in\ h_p$ **do**
4: **Compute** $ChIn$ between j_p and j_{p+1} that fulfills $ch\_Rank\ \geq\ CS_{threshold}$
5: $ChIn_j\ \leftarrow ChIn$
6: **end for**
7: **Construct** Path-channel logical tree from all $ChIn$
8: **Compute** all possible paths using DFS scheme ($Paths$)
9: **for** each $p \in Paths$ of hop-length h_p **do**
10: **Compute** $EPST_{\mathrm{p}}(\mathrm{t})$ Using Eq. (1)
11: **Calculate** N_p from path p
12: **Compute** $ST_i^{F_s}(t)$ using Eq. (19)
13: **Compute** $D_i^j(t)$ using Eq. (20)
14: **Compute** $D_p^{sw}(t)$ using Eq. (21)
15: **Compute** $EDP_p(t)$ using Eq. (22)
16: **Compute** $PLR_p(t)$ using Eq. (23)
17: **Compute** $A_p^{br}(t)$ using Eq. (24)
18: **end for**
19: **end for**

VI. Performance Analysis

For the performance analysis of the proposed scheme, we perform extensive experiments in C language by using High Definition (HD) video with 720p and Low Definition (LD) video with 360p. The performance is measured in terms of channel rank, EPST, PLR, throughput, EPD, and PSNR. Moreover, to show the performance gain of the proposed scheme, we compare the results with the conventional non QoS-based scheme.

A. Simulation Results

Channel rank provides the statistics about the quality of channel. The higher channel rank means better channel quality and lower channel rank means poor channel quality. Therefore, a channel with higher rank is selected in the proposed scheme to reduce the interference with the

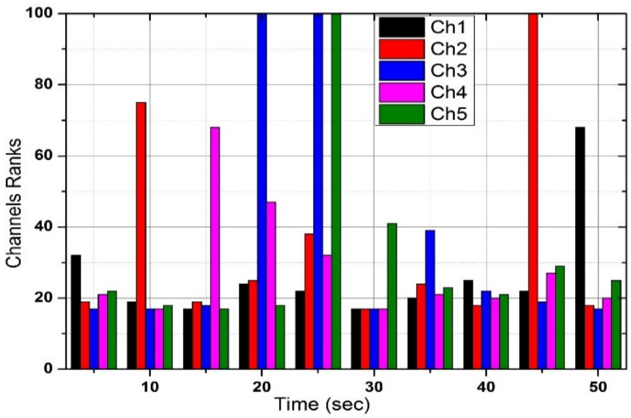


Figure 6: Channel ranking.

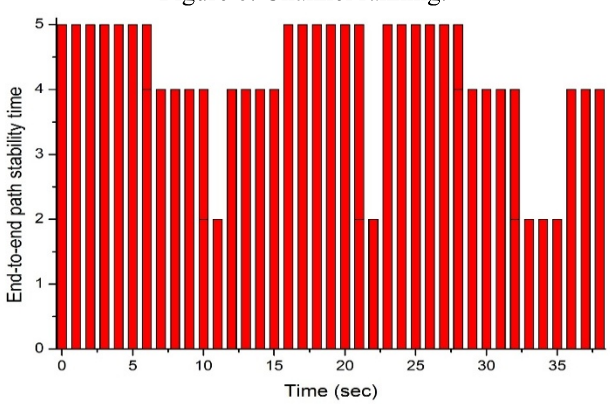


Figure 7: End-to-end path stability time.

PU as well as reduce the channel switching rate. Fig. 6 shows the channel rank values over time. Fig. 7 shows the number of times the selected path has broken due to the PU occurrence. Fig. 8 shows that the proposed scheme experiences the few path breaks as compared to the non-QoS based scheme. End-to-end path stability time provides the time value for which the routing path is safe (i.e., SU transmissions without PU's disturbance) and the best path is selected who provides the higher value of EPST. It is calculated after the constructing multiple paths according to Eq. (1). Fig. 7 presents the plot for the EPST. End-to-end PLR is also calculated after the constructing multiple paths for multimedia data routing and the best path is selected which provide the lowest value of the end-to-end PLR value which means the quality of the multimedia transmission over this path will be better. It is clear from the Fig. 9 that the proposed scheme helps to select the path with lower end-to-end PLR as compared to the non-QoS based scheme.

End-to-end bitrate which can also be measured as throughput over the selected paths is calculated based on the supported bitrates by individual links. Thus, a best path is considered that provides a higher end-to-end bitrate value which means the path can support better quality of multimedia transmissions.

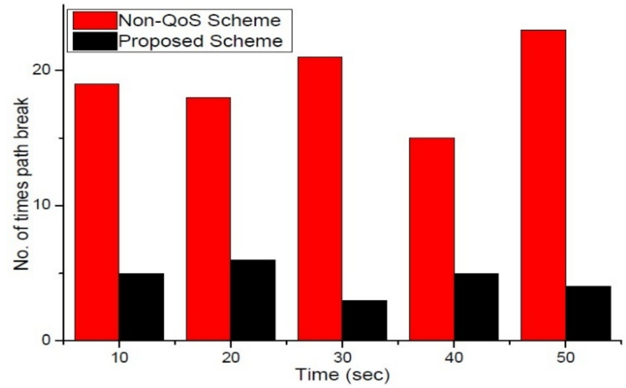


Figure 8: No. of time path breakage occur.

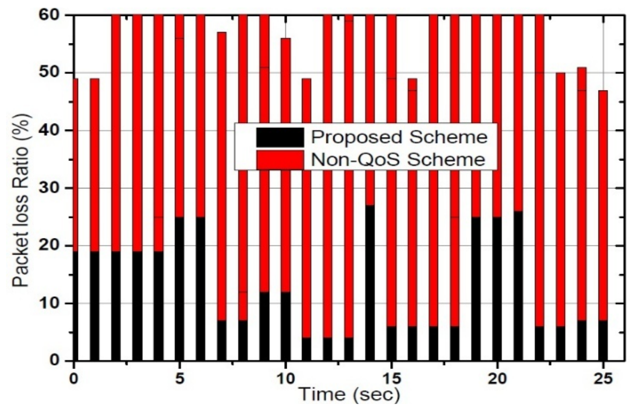


Figure 9: Packet loss ratio.

Fig. 11 represents the end-to-end value of the bitrate supported by the channel over a time span of 50 sec. value which means the path can support better quality of multimedia transmissions. Fig. 11 represents the end-to-end value of the bitrate supported by the channel over a time span of 50 sec. With this information the bitrate of the multimedia is adjusted at sending time to avoid unnecessary packet loss and network congestion. Moreover, based on the available information the sender SU can decides either to send base frame only or both the base frame and extended frame. Similarly, end-to-end path delay metric helps to selects the best path from the pool of available paths based on the end-to-end delay value. For multimedia transmissions a path that support lower end-to-end delay is preferable. Fig. 10 represents the plot of end-to-end delay of PU channels over a time span of 50 sec.

An informal or a formal measure of processed/transmitted video quality is typically compared with the original video. So, for calculating degradation of video we calculate PSNR for that video. If the PSNR value of degraded video remains between 20db to 40db the quality is good. Fig. 12 presents the graph for transmission of HD video using QoS parameters qualified path and non-qualified path. PSNR for QoS parameters qualified path remain between 35db to 40db. While for non-qualified path PSNR value fluctuate randomly that mains quality of video is very bad. Similarly, Fig. 13 presents the plot for the multimedia transmission of

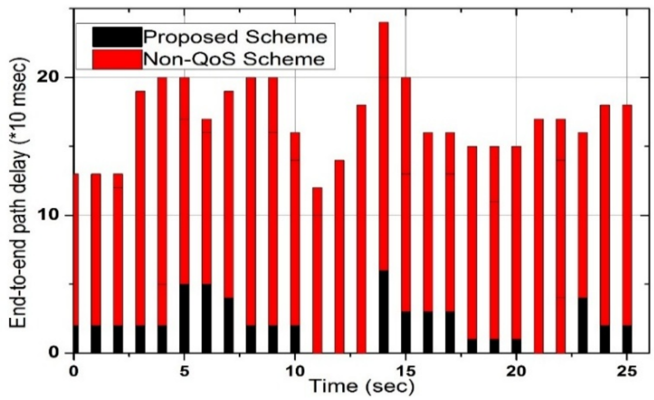


Figure 10: End-to-end path delay.

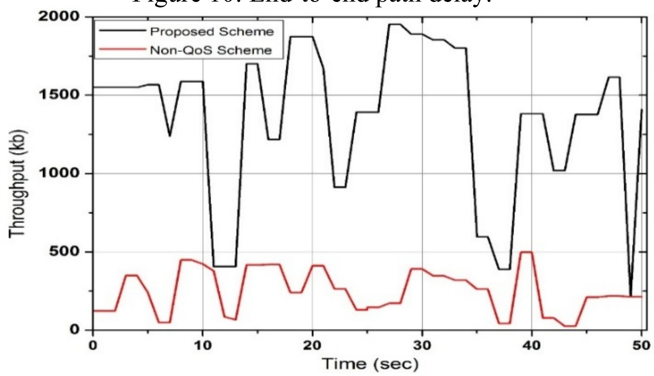


Figure 11: Throughput.

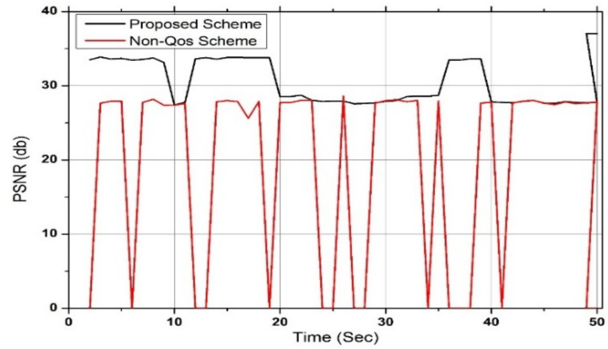


Figure 12: PSNR high definition video.

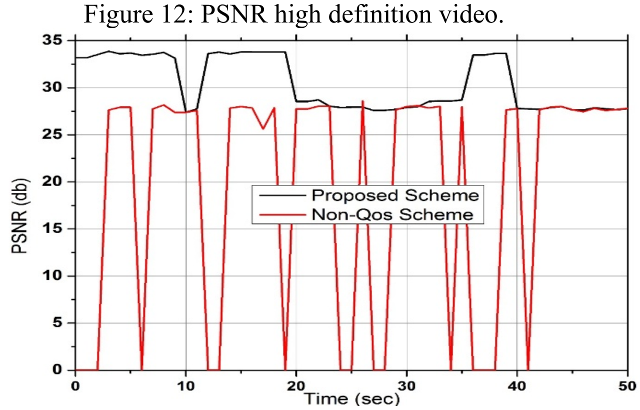


Figure 13: PSNR low definition video.

low definition video using QoS parameters. Thus, the PSNR for QoS parameters qualified path remain between 27db to 34db. While for non-qualified path PSNR value fluctuate randomly that means the quality of video is poor. Fig. 14 a-b display the effect of the received video at receiver for both proposed scheme and for conventional or non-QoS based scheme. Hence, it is clear from the figures that the proposed scheme supports better video quality at the receiver.

(a) Proposed scheme

(b) Non QoS-based scheme.

Figure 14: Proposed vs. non-Qos based scheme

VII. Conclusion

Multimedia transmissions over multi-hop CRNs is challenging task especially when the quality of the video is needed not be to degraded below a certain QoS threshold. Thus, in this paper, we proposed a cross layer routing scheme for transmitting adaptive bitrate video over MCRNs. In the proposed scheme, the best path is selected based on the higher value of the EPST and lower value of the EPD along with the RM QoS requirements. Further, in order to ensure the path continuity, to avoid the interference with the PU, and to improve the channel utilization, and error resilience over time varying PU licensed channels, we introduced a periodic path updation scheme. Simulation study shows that the proposed cross layer routing scheme based on the periodic path updation mechanism is more robust and suitable for supporting the RM transmissions over dynamic natured MCRNs.

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