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Abstract—This paper presents a cross-layer design for a reliable video transmission over wireless ad hoc networks based on multichannel MAC protocol with TDMA. First, we conduct a study of the multichannel MAC protocol through Markov chain model. Based on this study, two novel cross-layer modules are adopted for the design of multichannel MAC protocol. First, we adopt maximum latency rate (MLR) as the channel quality metric. Unlike the traditional MAC design based on network allocation vector (NAV), MLR is implemented to provide differentiated traffic so that the channel with smaller MLR time is initiated for higher priority traffic. Second, we adopt two congestion-aware metrics, namely MAC utilization and queue length of MAC layer, to improve the congestion-aware routing protocols with AODV and DSR. These two novel modules allow the proposed MAC protocol design to achieve high performance video transmission over wireless ad hoc networks. Experimental results show that the proposed scheme outperforms the state-of-the-art schemes under multichannel environments in wireless ad hoc networks for as much as 3.6 dB in PSNR. Such significant performance enhancement confirms that the cross-layer approach is very effective for multichannel MAC protocol design.

Index Terms—Cross-layer design, H264/AVC, maximum latency rate (MLR), multichannel MAC, network allocation vector (NAV), TDMA MAC.

I. INTRODUCTION

With recent advances in wireless mobile ad hoc network (MANET) and the proliferation of H.264 video coding standards, video streaming is becoming common for wireless ad hoc networks. Without integrated access points or base stations, mobile stations in MANET can communicate with each other directly under power constraint, intervention, and channel effect limitations. Even though current IEEE 802.11a/b/g/n physical layer (PHY) [1] can support the use of multiple channels making use of multiple frequency bands without any obstruction with each other, mobile stations in ad hoc mode and infrastructure mode are often limited to one channel under current standard protocols [2]–[5].

In order to increase the throughput and to reduce the delay of the ad hoc networks, multichannel MAC protocols have been proposed in [6]–[8]. Unfortunately, these protocols cannot be directly adopted to achieve higher quality delivery of time-bound applications such as VoIP and video streaming [6]–[11], [13] because these time-bound applications also require stringent quality-of-service (QoS) constraints such as video packets loss rate, throughput, and packet delay. Most of these existing approaches in multichannel MAC only showed improved throughput comparing with single channel MAC. Existing research in QoS driven H.264 transmission over wireless ad hoc networks [2], [3], on the other hand, have assumed only single channel MAC with IEEE 802.11e standard [4].

It is clear that multichannel MAC protocol design will benefit from a cross-layer design, especially for time-bound video streaming applications, since the overall QoS of time-bound applications depends on multiple QoS metrics including throughput, packet loss rate, and packet delay [6]. Multichannel MAC architecture will be able to support the specified channel for video packet without contention and reduced congestion in MAC layer level in order to minimize the video packet loss rate. A cross-layer design also provides the wireless channel information and the status of the lower level through all layers up to the application layer (video packets) to reduce the video packet loss rate. However, there have been little research to take full advantage of both cross-layer and multichannel design [10], [11] and explicitly consider the QoS constraints for time-bound applications.

Among the existing approaches, the authors in [6] presented various analysis and simulations based on several existing multichannel MAC protocols. They categorized these protocols into four classes as dedicated control channel, common hopping, split phase, and multiple rendezvous. They compared the performances of multichannel protocols with respect to the effects of the number of channels, channel switching times, and traffic patterns on throughput and delay. However, these analytical models for the four protocols using Markov chains cannot be adopted directly for video streams with cross-layer coupling since the evaluation of packet loss impacts on video reception is not straightforward.

Recently, Zhang et al. proposed a TDMA-based multichannel MAC (TMMAC) protocol over ad hoc networks [7]. It was shown that TMMAC can automatically adapt its negotiation window size depending on different traffic patterns. With such adaptation, TMMAC not only performs up to 113% higher communication throughput but also dissipates 74% less energy per
packet with single-transceiver wireless devices. However, this scheme lacks adequate strategy for the transmission of time critical application and for the cross-layer design.

In [8], the authors investigated the congestion mechanisms such as longest queue first (LQF) and random scheduling to avoid the channel congestion. They also presented their MAC protocol designs and the validation of the design using simulation and implementation. However, they have not considered the special characteristics of delay sensitive applications such as audio and video streaming over wireless ad hoc networks.

More recently, Yang et al. proposed in [12] an adaptive video transmission scheme to achieve an unequal error protection in the multichannel ad hoc networks. Their research is limited to unequal error protection and video streams coded by the MPEG-2 making use of only simple error resilient means in data partition. The partition of video stream into high priority and low priority portions enables the scheme to match with multichannel configuration for video transmission. Simple channel quality measure called busy time ratio is applied to characterize the channel link status. The lack of cross-layer strategy and state-of-the-art H.264 video coding standard [14] diminishes the possibility of adopting this approach to contemporary video streaming over multichannel ad hoc networks and the potential impact of this scheme.

In summary, various existing schemes have attempted to develop multichannel-based approaches to enhance the performance of the wireless ad hoc networks. The lack of consideration for time-bound applications and for cross-layer strategy makes them unrealistic to be adopted for video streaming over MANETs. Therefore, there is a pressing need to design a cross-layer approach that is suitable for time-bound applications in video streaming by taking full advantages multichannel MAC protocols.

The rest of this paper is organized as follows. In Section II, we first present the architecture of the multichannel MAC based on TDMA. We then introduce the definition of several key parameters for the analysis of proposed multichannel TDMA MAC protocol. In Section III, we first illustrate the proposed cross-layer design strategy for multichannel TDMA MAC protocol. We then present the investigation of the packet loss effect on the received video quality based on the pixel-level loss-impact (PLI) metric. In Section IV, we show the performance evaluation through both analysis and simulation based on H.264 video streaming [14]. Section V summarizes this paper with some discussions.

II. ARCHITECTURE AND ANALYSIS OF MULTICHANNEL MAC

A. Multichannel-Based TDMA MAC Architecture

This section illustrates the proposed multichannel ad hoc network based on TDMA to investigate the advantage of both multiple channel and TDMA. Although the proposed MAC design is closely related to both MMAC [13] and TMMAC [7], this work is fundamentally different from TMMAC [7] because the TMMAC lacks flexible MAC to integrate the wireless channel information which is crucial for cross-layer design.

We only follow the main MAC architecture based on the TMMAC while innovatively integrating several models for the proposed cross-layer design. The architecture is also based on a single half-duplex transceiver and IEEE 802.11 distributed coordination function (DCF) protocol [4]. In the MAC protocol design, in order to achieve higher throughput and lower packet delay, depending on the feedback of traffic patterns, a beacon interval is divided into fixed phases, consisting of an ad hoc traffic indication messages (ATIM) window and followed by a communication window. The communication window is called time slot, with its period duration necessary for packet transmission. Through the ATIM window, each station is not only able to select which time slots to use for the desired data communication but also which channels to employ for the intended data communication. Fig. 1 illustrates the proposed architecture for multichannel TDMA MAC.

III. PARAMETERS FOR ANALYZING MULTICHANNEL MAC PROTOCOLS

In order to take advantage of embedded error resilience in H.264 video coding standard and the flexibility of multichannel operation, a measure of the channel quality needs to be defined appropriately. In this research, instead of applying network allocation vector (NAV) as defined in conventional MAC design, we propose to define maximum latency rate (MLR) to characterize the quality of the channel. MLR is defined as the total time that a physical channel experiences latency regularized by the measured time. Such definition indicates that channels with smaller value of MLR shall provide better link quality for video streaming. With such an MLR definition, the channel quality information from the physical layer can be applied in MAC layer and the queue length information from network layer can be adopted as the adaptive metric for cross-layer design. Furthermore, the congestion information and MAC layer utilization from the MAC layer can be applied in the network layer without increasing overhead. As a result, the proposed MLR is able to differentiate video traffic as the higher priority ones than the general data transmission for prioritized transmission.

For H.264 encoded video stream, high priority traffic should be directed to channels with low MLR while low priority traffic should be directed to channels with high MLR. Adopting MLR as channel quality metric, we can design robust H.264 video streaming multichannel ad hoc networks. Fig. 2 illustrates the concept of MLR and possible application of MLR in prioritized media streaming. To estimate the capacity of multichannel-based TDMA MAC, we present here a mathematical analysis of the saturated throughput and delay profile for both multichannel TDMA and single-channel MAC in IEEE 802.11.
of a packet is the average amount, the expected value of and stands for the probability that a transmission from (1) and (2). Note that and are in [0, 1].

Let denote the probability that there is at least one station within a time slot, and is the probability that a transmission is successful. They can be expressed as

\[
p_{tr,i} = (1 - (1 - \tau_i)^{N_i}) \prod_{h=1, h \neq i}^N (1 - \tau_h)^{n_h}
\]

\[
p_{hs,i} = \frac{1}{(p_{tr,i})}
\]

For simplicity, we can represent the saturation throughput based on the access mechanism of IEEE 802.11 as the ratio in (5) at the bottom of the page, where \(E[P]\) is the video packet payload size, \(p_{tr,i} \cdot p_{hs,i} \cdot E[P]\) is the average amount of successfully transmitted payload information. The average length of a time period consists of \(E[T]\), the expected value of an empty slot time, and \(p_{tr,i} \cdot p_{hs,i} \cdot T_{c,i}\) is the time that a successful transmission without collision, and \(p_{tr,i} \cdot (1 - p_{hs,i}) \cdot T_{c,i}\) is the time that a successful transmission with collision. Suppose that \(R_{TDMA}\) represents bit rate, in which \(M\) is the number of channel [15]. For simplicity, we assume that maximum \(R_{TDMA}\) equals to the average maximum saturated throughput, which can be denoted as \(ST_{TDMA}\) at the bottom of the page.

To determine the throughput, we also need the corresponding values \(T_{c,i}\) and \(T_{s,i}\) in terms of single-channel and multichannel, respectively. These parameters can be defined as in (8) at the bottom of the next page, where \(H\) stands for the physical and MAC layer headers. In addition, \(P\) is the video payload size.

Moreover, we also carry out the packet delay analysis for multichannel TDMA MAC protocol in comparison with that of single-channel MAC. Such analysis is based on the studies we carried out in our previous research [4], [5]. The saturation delay \(S_{Di,j,k}\) is defined as an average time interval until it is successfully transmitted. When the packet transmission has reached the preset retry limit, it will be dropped. The average saturation delay \(E[S_{Di,j,k}]\) of single channel is defined as

\[
E[S_{Di,j,k}] = E[X_i] \cdot E[length of a slot time]
\]

The table shows the definitions of system parameters used in analysis.

**TABLE I**

<table>
<thead>
<tr>
<th>Terms</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_i)</td>
<td>Number of stations contending for the channel</td>
</tr>
<tr>
<td>(\tau_i)</td>
<td>A station transmits a packet in priority i during slot time</td>
</tr>
<tr>
<td>(p_{tr,i})</td>
<td>Probability that at least one station try to transmit a packet</td>
</tr>
<tr>
<td>(p_{hs,i})</td>
<td>Probability that a current packet transmission is successful</td>
</tr>
<tr>
<td>(T_{s,i})</td>
<td>Time spent in a successful transmission</td>
</tr>
<tr>
<td>(T_{c,i})</td>
<td>Time spent in a collision</td>
</tr>
<tr>
<td>(R)</td>
<td>Retry limit and maximum backoff stage</td>
</tr>
</tbody>
</table>

WLANs are based on Markov chain model presented in [4] and [5]. Table I lists the definitions of system parameters used in the analysis.

The study based on WLAN offers easier understanding for multichannel TDMA since multithop ad hoc networks are more complicated than WLAN. We have developed the analytical model based on the Markov chain model for IEEE 802.11e enhanced distributed channel access (EDCA). In order to compute the saturated throughput and delay for multichannel networks, we need to adopt the analytical model developed previously in [4] and [5] based on the distributed coordination function (DCF) MAC mechanism. When we consider the relation between packet size and saturated throughput, we shall attempt to find the optimal trade-off between them.

We first assume that every station always has an available packet for transmission in which the probability \(\tau_i\) of a packet being transmitted from a station in a slot can be represented as

\[
\tau_i = \sum_{j=0}^{R_i} b_{i,j,0} = \sum_{j=0}^{R_i} p_{i,j} \cdot b_{i,j,0} = 1 - \frac{p_i^{R+1}}{1 - p_i} \cdot b_{i,0,0}
\]

where \(b_{i,0,0} \cdot b_{i,j,0}\) represent the initial and j stage, \(p_i\) stands for the probability that a transmitted packet encounters a collision (the channel busy probability) when two or more stations try to transmit their packets. \(p_i\) can be defined as

\[
p_i = 1 - (1 - \tau_i)^{N_i - 1} \prod_{h=1, h \neq i}^N (1 - \tau_h)^{n_h}
\]

Based on [4], we can easily calculate the two parameters \(\tau_i\) and \(p_i\) from (1) and (2). Note that \(p_i \in [0, 1]\) and \(\tau_i \in [0, 1]\).

Fig. 2. Maximum latency rate (MLR) for data channels.
where $E[X_i]$ is the average time interval required for effectively transmitting a packet. We can finally derive

$$E[X_i] = \sum_{j=0}^{R} \left[ \frac{(p_i^j - p_i^{R+1}) \cdot W_{i+1}}{1 - p_i^{R+1}} \right]$$ (11)

where $(1 - p_i^{R+1})$ is the probability that the packet is not dropped since the packet drop probability is equal to $p_i^{R+1}$. In other words, when retransmission of data packet reaches the preset retry limit (commonly 7), it is noticeably dropped. $(p_i^j - p_i^{R+1})/(1 - p_i^{R+1})$ is the probability that a packet that is not discarded and reaches the $j$ stage.

To estimate saturation delay for multichannel TDMA MAC, we can adopt the fundamental principle of TDMA scheme [15]

$$D_{TDMA} = w(\text{latency time}) + \tau(\text{transmission time})$$ (12)

$$w = \frac{1}{M} \sum_{m=1}^{M} (m - 1) T = \frac{T}{M^2} \sum_{m=1}^{M-1} m$$

$$w = \frac{T}{M^2} (M - 1) M$$

$$\tau = \frac{T}{2} (1 - \frac{1}{M})$$ (13)

$$D_{TDMA} = \frac{T}{2} (1 - \frac{1}{M}) + \frac{T}{M}.$$ (14)

We assume that the average saturation delay $E[SD_{i,j,k}]$ equals to total time $T$ according to $D_{TDMA}$ as defined above. As a result, we can derive the average saturation delay of multichannel TDMA MAC ($E[SD_{TDMA}]$) as the parameters for the multichannel

$$E[SD_{TDMA}] = \frac{E[SD_{i,j,k}]}{2} \left( 1 - \frac{1}{M} \right) + \frac{E[SD_{i,j,k}]}{M}.$$ (15)

Fig. 3 shows the analytical and simulation results of the saturation throughput for both single channel and multi channel scenarios, in which “Anal” and “Sim” represents the numerical results and the simulation results, respectively, under the assumption that video packets are transmitted at 200 kbps. It is obvious that the multichannel scenario outperforms the single-channel scenario for over two times even before a cross-layer design is applied. Furthermore, the cumulative distribution functions of the saturation delay as shown in Fig. 4 demonstrate the superior performance of multichannel scenario. With multichannel, over 90% of the video packets have a delay less than 0.4 s (the desired video delay constraints).

$$T_{c}^{\text{single}} = \text{RTS} + \text{SIFS} + \text{CTS} + \text{SIFS} + H + P + \text{SIFS} + \text{ACK} + \text{DIFS}$$ (8)

$$T_{c}^{\text{TDMA}} = \text{ATIM} + \text{SIFS} + \text{CTS} + \text{SIFS} + H + P + \text{SIFS} + \text{ATIMACK} + \text{DIFS}$$

$$T_{c}^{\text{single}} = \text{RTS} + \text{SIFS} + \text{CTS} + \text{timeout} + \text{DIFS}$$

$$T_{c}^{\text{TDMA}} = \text{ATIM} + \text{SIFS} + \text{CTS} + \text{timeout} + \text{DIFS}$$ (9)
IV. CROSS-LAYER DESIGN STRATEGY AND ANALYSIS

A. Proposed Cross-Layer Design Strategy

To improve the overall QoS metrics of the time critical applications, it is desired to design a cross-layer strategy for H.264 video transmission over ad hoc networks. There are many existing cross-layer QoS design approaches that can be categorized as top-down approach, bottom-up approach, application-centric approach, MAC-centric approach, and integrated approach [16], [17]. We believe that a MAC-centric approach offers flexible design for traffic admission control from the MAC layer to the application layer. Such approach enables cross-layer design to optimize the H.264 video transmission over ad hoc networks. The proposed MAC-centric approach to video streaming over wireless ad hoc networks is shown in Fig. 5.

The proposed approach shown in Fig. 5 (the overall architecture) and Fig. 6 (the network stack) is based on two congestion-aware metrics. In this research, we employ a congestion-aware cross-layer interaction system that consists of MLR and congestion-aware optimizations to improve the overall performance in terms of throughput, packet lost rate, and latency. With MLR scheme, the channel quality information from physical layer is used in MAC layer; or the queue length information from network layer is used as the adaptive metric. By congestion-aware scheme, the congestion information–MAC layer utilization from MAC layer is used in network layer. We illustrate our cross-layer system in the flow diagram in Fig. 6.

First, we take MLR as an indicator for congestion. We assume that the congestion information can be calculated at a station. When the MLR of MAC layer is less than given thresholds, average MAC layer utilization is defined as 0. On the other hand, when the MLR of MAC is larger than given thresholds, MAC layer utilization is 1. Since the MAC layer utilization is either 1 or 0, in order to obtain the use percentage of the wireless medium, we need to measure the average value within 1 s in our simulation. Such scheme is similar to the one presented in [18].

Second, we take instant queue length as another indicator for congestion. In other words, if a station has many packets remaining in the queue, it may lead to long packet latency or even dropping of packets. Such a phenomenon is critical to support the QoS of multimedia communication. Therefore, the queue length is indeed another good congestion indicator for video streaming over ad hoc networks.

Finally, we modify the route discovery mechanism to include the congestion information in routing protocols (AODV and DSR). For example, when an intermediate station obtains a route request (RREQ) packet from transmitting source station, it will include the congestion metrics. Whenever the combined congestion metrics are higher than given thresholds, then, that will signify higher level of congestion around the station. Conventional approaches to forward RREQ packet to other stations will intensify the congestion in two ways. First, the transfer of this RREQ packet will increase the utility of the medium around the congested spot. Second, the transfer will result in a new route across the busy region and lead to extra transmission burden.

Instead of switching and forwarding this RREQ packet, the busy station will just drop the packet. With this drop, source station may accept the route reply (RREP) from other non-congested stations or open a new route discovery for the same destination and obtain newly discovered optimal routes that will avoid the congested stations. The flow of these operations is shown in Fig. 7. As a result, the proposed scheme (modified AODV and DSR) employing congestion metrics is able to return less congested routes, rather than the shortest routes. This approach decreases the total latency and enhances the load balance of the overall ad hoc networks. The total delay of a packet shall contain queuing delay, transmission delay, and processing delay. When a packet moves through the longer but less congested routes, the transmission delay may increase but the queuing delay time will decrease due to shorter queues of the intermediate nodes. Suppressing RREQ forwarding may be unable to determine the path to target node when a route actually exists but goes through the congested area. Forcing the route to avoid the congested area may cause a node to discover a longer but less traveled route. Even though this leads to extra traffic overhead to other fractions of the network, it actually results in the desired load balancing. In this case, we have to keep the route maintenance mechanism part of ad hoc routing protocols.

In addition to the application of channel information as well as the two congestion-aware metrics through cross-layer coupling, adaptive FEC algorithm is also employed to ensure higher quality video transmission in the application layer. We will confirm, both theoretically and experimentally, the proposed cross-layer design that makes use of MLR as channel metric and two congestion-aware metrics for routing. These new metrics
are more flexible for wireless channel and the congestion handling and the percentage of the overhead is similar to the regular schemes under similar simulation topology.

B. Evaluation of Packet Loss Impacts

When a packet of video data is lost, its impact on the overall video quality needs to be evaluated for any QoS driven approach. In this research, we shall investigate the effect of each lost packet as defined in [21] that describes the pixel-level loss-impact (PLI) metric as the product of two parameters: pixel reference count (PRC) and pixel-wise concealment error (PCE) as defined in the following:

\[
PLI(t, x, y) = PCE(t, x, y) \cdot PRC(t, x, y)
\]  

(17)

where in the motion-compensated prediction (MCP) procedure as illustrated in Fig. 8, it is assumed that frame \( n \) is the last frame of a GOP and the numbers in the braces denote the PRCs of pixels showing the frame dependency on each other. \( PRC(t, x, y) \) stands for the frequency of pixel \((x, y)\) in frame \( t \) that is referenced by pixels of the following frames within a GOP. From frame \( t + 1 \) to the last frame of the GOP which may directly or indirectly reference pixel \((x, y)\) of frame \( t \) in an inverse tracking order, PRC can be computed recursively by the summation of individual reference counts of pixels; see (18) at the bottom of the page, where \( N_{GOP} \) describes the GOP size.

PCE is defined as the norm of concealment error for pixel \((x, y)\) in frame \( t \) with distortion

\[
PCEE(t, x, y) = |f(t, x, y) - f(t - 1, x, y)|^2
\]  

(19)

where \( f(t, x, y) \) stands for the pixel value at pixel \((x, y)\) in frame \( t \). We assume that the zero-moment error concealment scheme is applied.

The macroblock-level loss impact can then be estimated as

\[
PLI_{MB}(t, v) = \sum_{(x, y) \in MB_v} PLI(t, x, y)
\]  

(20)

where \( v \) denotes the macroblock index in a frame and \( t \) is the time index of frame, \((x, y)\) denotes the pixel coordinate, and \((MV_x, MV_y)\) is the associated motion vector of pixel \((x, y)\). Therefore, all \( PLI_{MB} \) in one packet can be added up to estimate the packet-level error propagation as follows:

\[
EPIL_{pkt}(k) = \sqrt{\sum_{MB_v \in packet \ k} PLI_{MB}(t, v)}
\]  

(21)

where \( k \) denotes the packet index of a frame.

The above scheme of loss impact estimation is simple yet effective to support the QoS driven real-time video streaming over wireless ad hoc networks. We apply the loss impact estimation in application layer to implement an adaptive FEC scheme in response to the time varying link status for the wireless channel in ad hoc networks. The estimation of loss impact as outlined above has been validated to be effective in [21], and the application of such estimation scheme for the proposed cross-layer design can be justified.

In this research, the estimation of the loss impact has been integrated with adaptive FEC to achieve improved QoS performance. We adopt Reed–Solomon for FEC design and the rate adaptation is governed by the PLI parameters by changing the partial stream redundancy field of R-S codes. In particular, the rate allocations between source and channel coding can be implemented via the FEC design with a transmission frame size of \( n \) with RS \((n, k)\) codes in the application layer.

V. EXPERIMENTAL RESULTS

In this research, simulations have been carried out to compare the performance of conventional multichannel schemes (MMAC and TMMAC) with that of the proposed multichannel based TDMA with cross-layer design for video streaming over ad hoc network applications. In particular, we implemented the simulation topology that consists of 20 mobile stations with non-overlapping three-channel scenario based on the random distribution in a 500 m x 500 m square area. The bit rate is at

\[
PRC(t, x, y) = \begin{cases} 
\sum_{(t+1, x', y') \to (t, x, y)} PRC(t+1, x', y') & 1 \leq t < N_{GOP} \\
1 & t = N_{GOP}
\end{cases}
\]  

(18)
1 Mbps for each channel, and several system parameters are based on physical layer parameters used in the IEEE 802.11b standard. In addition, in order to implement more complicated channel model that is close to practical network setting, we adopt the Rayleigh fading statistical channel [19] in combination with the finite-state Markov chain channel models [20]. This is more realistic than existing approaches [6]–[13] which have not considered the impact of wireless fading channel on video transmission quality over wireless ad hoc networks.

At the higher layer, we also modified the routing protocols AODV and DSR to accommodate the cross-layer design. The test video sequences are *Highway* (2000 frame) and *Carphone* (360 frame) with baseline profile (I and P frames). In the simulation, we are able to assign the video sequence to higher quality channel among the three channels based on the proposed multichannel-based TDMA with the cross-layer design.

We assume that all mobile stations are communicating with multihop protocol in ad hoc networks. Background UDP (18 stations) is also included with the size of packet at 512 bytes and transmission rate at 600 Kbps. We conduct the simulations using the NS-2 simulator [22] and the simulation time lasts for 100 s. The results are averages obtained over ten simulations.

Fig. 9 shows the saturated throughput performance of proposed approach with and without cross-layer design and compared with TMMAC, MMAC, and standard IEEE 802.11 at different network loads. Initially, these five different MAC protocols achieve similar aggregated throughput. However, as the network load increases, TMMAC and the proposed cross-layer-based scheme outperform MMAC and 802.11 standards. The proposed multichannel-based TDMA with cross-layer design achieves two times more aggregated throughput than the existing MMAC as well as the proposed multichannel approach without cross-layer design.

Fig. 10 illustrates the saturated packet transmission delay performance of these five MAC protocols. Note that in Fig. 10, TMMAC achieves the best saturated packet delay among all five MAC protocols. It can be observed that the proposed model experiences more saturated packet delay than the MMAC and TMMAC schemes because it may utilize long path, instead of short path in order to avoid congested station areas which may eventually result in reduced packet loss rate. However, the proposed multichannel scheme is designed to meet the delay constraint of real-time video streaming.

Fig. 11 shows the comparison of packet loss results from all five MAC protocols. The proposed loss impact estimation as it applied to all five protocols has been calculated offline. Although the calculation of packet lost rate is an important metric for QoS performance in wireless video transmission, existing approaches have not considered such metric in their research [6]–[13]. We can see that the packet loss rate of the proposed multichannel cross-layer scheme outperforms existing multichannel schemes (MMAC and TMMAC).

Fig. 12 illustrates the performance of H.264 video streaming represented by typical frames of the reconstructed video at the receiving end. In the experiments, we adopt station mobility with the speed of 6 m/s under these five schemes. The experimental results indicate that the proposed approach outperforms the conventional multichannel MAC protocol scheme by an average of 3.6 dB in PSNR.
We believe the outstanding performance in improving the quality of video transmission is achieved by cross-layer design that offers positive interaction when time critical multimedia streaming application layer benefits from interaction with MAC and routing protocols under wireless fading channel models.

Table II presents the average reconstructed PSNR of two test video sequences under these five different approaches. For comparison purpose, Table II also includes the PSNR of these two video traces transmitted over error-free channels. Decoded frames of the Highway and Carphone sequences prove that the wireless video transmission systems using the proposed multichannel TDMA with cross-layer scheme achieve noticeable gain over all other schemes. Table II also shows that the proposed scheme performs close to error-free video transmission.

Fig. 13 presents in detail the time sequential PSNR measurements of H.264 video quality with reconstructed video streams under three representative schemes. Even though traditional multichannel MAC may support certain time bound applications such as VoIP and video, they are unable to satisfy overall QoS constraints, including packet loss rate and packet loss impact. In particular, both TMMAC and MMAC would lead to increase in packet loss comparing with the proposed scheme with cross-layer design. Therefore, the proposed multi-channel-based TDMA with cross-layer design is able to provide significantly higher video quality transmission as well as more stable PSNR traces for video over wireless ad hoc networks.
VI. CONCLUSIONS

In this paper, we have introduced multichannel based on TDMA with cross-layer design to achieve optimal QoS performances for reliable video transmission over wireless ad hoc networks. We studied thoroughly several networking metrics, including saturated throughput, packet transmission delay, and the packet lost rate by estimation of packet-level loss impact characteristics for multichannel MAC protocol with Markov chain model. Two important components of the cross-layer design have been developed in this research that are key to the success of this multichannel MAC with cross-layer design. First, instead of using network allocation vector as utilized in the traditional MAC, we have developed MLR as the channel quality metric in order to distinguish different video streaming traffic so that the channel with smaller MLR time is selected for higher priority traffic. Second, we have also adopted two congestion-aware metrics, MAC layer utilization and queue length of MAC layer, to enhance the congestion-aware routing protocols (AODV and DSR). The interaction of these two components enables the proposed scheme to achieve higher quality video transmission under more realistic wireless fading channel models.

Simulations based on NS-2 have been carried out to verify the performance of the proposed scheme. Experimental results confirm that the proposed scheme outperforms all other multichannel schemes, including IEEE 802.11 DCF, MMAC, TMMAC, and multichannel-based TDMA without cross-layer consideration. Moreover, the proposed scheme achieves high performance even when the wireless ad hoc channels are severely error prone. The average PSNRs of the reconstructed video test sequences are very close to the video transmission over error-free channels. In the future, we plan to study the inherent relationship between the dependency of video frames and the dependency of the Markov chain wireless channel modeling, so as to achieve additional performance enhancement.

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