OASIS : A Framework for Enhanced Live Video Streaming over Integrated LTE Wi-Fi Networks

Tarun Patidar, Thomas Valerrian Pasca S, and Bheemarjuna Reddy Tamma
Department of Computer Science and Engineering,
Indian Institute of Technology Hyderabad, India
Email:[cs17mtech11025, cs13p1002, tbr]@iith.ac.in

***Abstract*—Live Video Streaming has a strict low latency requirement. Current multipath techniques like Multipath RTP (MPRTP) and Multipath TCP (MPTCP) are not optimized to meet this requirement. This is especially true when they are operating over a wireless medium, whose channel conditions change very rapidly and unpredictably. These multipath techniques are unable to adapt quickly to the dynamic channel conditions. LTE WLAN Aggregation (LWA) is capable of dealing with this problem since it makes its decisions at the edge of the network. In this paper, we propose the bOunded delAy baSed steerIng with timelineSs (OASIS) framework over LWA for streaming live video with low latency. The OASIS framework comprises of a novel traffic steering algorithm, BOunded deLay based sTeering (BOLT). BOLT calculates the maximum traffic load which can be transmitted on each of the links (LTE and Wi-Fi) before the packets experience higher delay *i.e.,* above a certain delay threshold. OASIS also comprises of a timeliness model, which prioritizes the packets belonging to Intra-coded picture (I-frames) over other packets. OASIS is implemented and tested in NS-3. We use NS-3 in emulation mode which allows us to stream real videos over the simulated topology. OASIS is compared with MPRTP, LWA, LTE, and Wi-Fi. We show that the proposed framework performs 1.4× better than MPRTP. Also, it outperforms all the other comparative techniques when tested under different scenarios. These scenarios are designed to test the different techniques under rapidly changing wireless medium. We also show that the quality of the video improves with the inclusion of the timeliness model.**

I. Introduction

Every year Mobile data traffic is growing exponentially. The main constituent of this traffic is Video. As per Ericsson mobility report 2018, video constitutes 60% of the total mobile data traffic, and it is estimated to rise to 74% by 2024 [1]. One of the rising categories of video is live and interactive video. It is widely used on social media, with services like Facebook live and Linkedin live, which allow users to interact in real time with their followers. In the professional world live video is used for conducting interviews, webinars and meetings. With increasing smartphone sizes and resolutions, the demand for streaming of higher quality live videos has increased. But the current bandwidth available to mobile operators fails to meet the demand imposed by the increasing number of users. Currently, almost all smartphones support multiple radio access techniques like Wi-Fi, 4G, 3G, and Bluetooth. One solution to meet the bandwidth requirement is to utilize these multiple wireless links. Techniques that avail multiple links include MPRTP (Multipath RTP), MPTCP (Multipath TCP), and LWA (LTE WLAN Aggregation) [2] [3] [4]. MPTCP and MPRTP establish multiple TCP and UDP connections respectively, from the server to the client. In the case of smartphones, they utilize both Wi-Fi and cellular links. LWA also utilizes both LTE and Wi-Fi links simultaneously, but the main difference from MPTCP is that it maintains a single flow from the server and the flow is split at the LWA node.

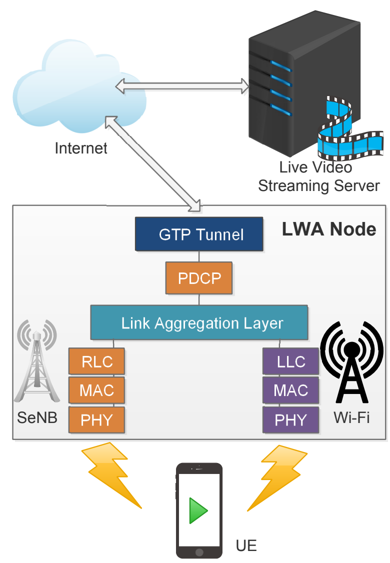


Figure 1: LTE Wi-Fi Aggregation Setup.

Figure 1 shows the LWA node, which integrates Small cell eNodeB (SeNB) and Wi-Fi AP in a node. LWA allows finer control over the wireless channels and also provides the benefit of aggregated bandwidth. Although these multipath techniques provide higher bandwidth, yet they are not optimal for streaming live video over the wireless medium. Live video imposes strict low delay requirements which are not met by default by all the techniques. In this paper, we propose OASIS (bOunded delAy baSed steerIng with timelineSs) framework for enhancing live video streaming over LWA. OASIS consists of (a) BOLT (BOunded deLay based sTeering) : a novel traffic steering algorithm and (b) a Timeliness model. BOLT steers traffic based on the traffic load that can be accommodable on each of the links before the delay experienced by packets exceed the delay threshold. It can also detect when to use only a single link as opposed to using both the links. The timeliness model reorders the transmission queues of LTE and Wi-Fi links at the LWA node when required, to try to prioritise the packets belonging to I-frames (Intra-coded picture) over other packets. We compare the performance of OASIS to MPRTP, regular LWA, only LTE, and only Wi-Fi. We show that LWA is better suited to live video streaming when the client is connected via the wireless medium. By steering traffic at the edge of the network, *i.e.,* at the LWA node, as opposed to all the way back at the server, OASIS reacts faster to the dynamic and unpredictable wireless medium.

II. Related Work

Real-time Transport Protocol (RTP) provides end to end support for live video streaming [5]. It operates over UDP, which provides low latency at the cost of reliability. RTP is typically used in conjunction with RTP Control Protocol (RTCP) which is used for Quality of Service (QoS) feedback. RTP is used by Web Real-Time Communication (WebRTC) [6]. WebRTC allows real-time communication between web browsers by providing simple application programming interfaces (APIs). But RTP is not built to operate over multiple paths and establishes only a single flow from the server to the client. MPRTP is designed to make RTP work over multiple paths. It splits the single flow of RTP into multiple subflows which are further transmitted over different paths. The flow distribution of the non-congested paths is determined by the ratio of bandwidth on a path to the total bandwidth available on each of the paths. LWA tightly integrates LTE and Wi-Fi links at the radio level. The traffic steering takes place at Link Aggregation Layer in the Packet Data Convergence Protocol (PDCP) of the LWA node. López-Pérez *et al.* try to optimally split traffic between LTE link and Wi-Fi link by using link delay estimates [7]. But their proposed flow control scheme is not optimal for live video as it does not take delay threshold into account. VISIBLE discusses two traffic steering algorithms [8]. First is Lowest RTT first (L-RTT). This steering algorithm first fills the transmit queue of the link with the lowest RTT before filling the queue of the other link. Second is Queue Depletion Rate (Q-Depl). Here the rate of depletion of queue sizes is used to split the traffic across LTE and Wi-Fi. Here are some works in literature which employed video transmission over multiple paths. ADMIT improves video quality over MPTCP by using Forward Error Correction (FEC) coding and a rate allocation scheme [9]. But this scheme works on top of TCP and TCP is not suitable for live video because of the added overhead of acknowledgements. J. Park proposes a traffic steering algorithm for DASH streaming over LWA [10]. But DASH is not suitable for live video since it operates on top of TCP and cannot provide sub-second latency required for real-time communication. In this paper, we have compared our work with LWA using L-RTT as the traffic steering algorithm and with MPRTP. To the best of our knowledge, none of the existing works has tackled the problem of streaming live video over LWA. Moreover, OASIS is the first LWA scheme that steers traffic based on the delay threshold and prioritizes I-frame packets over other frame packets. It is to be noted that OASIS does not deal with bitrate adaptation, and it is left to the application. OASIS is capable of operating under RTP and thus also works with WebRTC.

III. OASIS Framework

OASIS is a framework for streaming live video over LWA. It is implemented at the LWA node. OASIS consists of two major components : (1) BOLT: a novel packet steering algorithm, and (2) Timeliness model. The packet steering algorithm steers the incoming packets to the LTE and the Wi-Fi links respectively based on the link conditions. The timeliness model prioritizes I-frames over other frames of the video session.

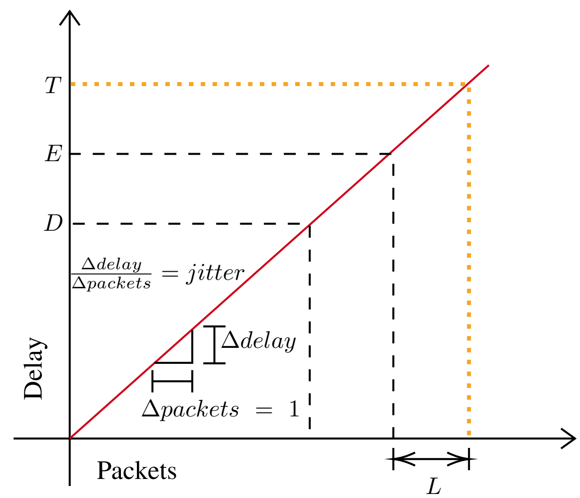


Figure 2: Per packet delay curve.

A. BOLT (BOunded deLay based sTeering)

BOLT is described in Algorithm 1. Table I describes the symbols used in the algorithm. BOLT decides the ratio of traffic which should be steered across LTE and Wi-Fi links. The steering ratio is determined based upon how many packets can be transmitted on each of the links before exceeding the delay threshold. Figure 2 shows a typical rise in the delay observed per packet. Here D represents the delay experienced by the last packet that was received on the link. BOLT calculates E, the estimated delay of the last packet that was transmitted on the link but is yet to be received. This estimation is done with the help of the slope of the curve or the jitter in this case. E is calculated as follows.

$$E_i = D_i + J_i \times (S_i - R_i); i \in \{lte, wifi\} \tag{1}$$

J_i is the exponentially averaged jitter. Jitter is only recorded if the current delay is greater than the previous delay *i.e.,* it

Table I: Symbols for the traffic steering algorithm

Symbol	***Description***
D_i	Delay of the last received packet on link i. $i \in \{lte, wifi\}$
J_i	Exponential average of the increasing jitter observed on link i. $i \in \{lte, wifi\}$
S_i	Number of packets sent so far on link i. $i \in \{lte, wifi\}$
R_i	Number of packets received so far on link i. $i \in \{lte, wifi\}$
E_i	Estimated Delay of the last packet sent on link i that is yet to be received. $i \in \{lte, wifi\}$
L_i	Load that can be transmitted on link i. $i \in \{lte, wifi\}$
T	Delay threshold, a packet expires if its delay exceeds this threshold.
A	amount of traffic that is to be steered towards LTE link.
B	amount of traffic that is to be steered towards Wi-Fi link.
$ratio$	ratio of A to B, it represents the traffic steering ratio.

represents the rate of increase of delay. S_i is the number of packets that have been sent on each of the links so far. R_i is the number of packets that have been received at the UE by each of the links. The UE periodically provides D_i, J_i, and R_i to the sender. T shows the delay threshold. All packets should be delivered without exceeding this threshold. BOLT calculates L, the max number of packets that can be transmitted on the link without exceeding T. L is calculated as follows.

$$L_i = \frac{T - E_i}{J_i}; i \in \{lte, wifi\} \tag{2}$$

L can be negative for a particular link if E exceeds the threshold. In this case, the other link should be used. If L is negative for both the links, then, in that case, the only option is to minimize the damage. This is done by steering more across the link with the lesser negative value of L. The steering ratio is calculated by dividing A and B. Here, A is the load that should be put on the LTE link and B is the load that should be put on the Wi-Fi link. A and B are calculated in Algorithm 1. The steering routine as shown in Figure 3 is executed at an interval of 't' ms at the LWA node. This interval is chosen based on empirical results; the interval can vary dynamically based on the variations observed on the channel.

Algorithm 1 BOLT (Packet Steering Algorithm)

Require: $D_{wifi}, D_{lte}, J_{wifi}, J_{lte}, S_{wifi}, S_{lte}, R_{wifi}, R_{lte}, T$

$E_{wifi} \leftarrow D_{wifi} + J_{wifi} \times (S_{wifi} - R_{wifi})$
$E_{lte} \leftarrow D_{lte} + J_{lte} \times (S_{lte} - R_{lte})$
$L_{wifi} \leftarrow \frac{T - E_{wifi}}{J_{wifi}}$
$L_{lte} \leftarrow \frac{T - E_{lte}}{J_{lte}}$
if $L_{wifi} \leq 0$ & $L_{lte} \leq 0$ **then**
    $A \leftarrow L_{wifi}$; $B \leftarrow L_{lte}$
else if $L_{wifi} \leq 0$ **then**
    $A \leftarrow L_{lte} + (-1 \times L_{wifi})$; $B \leftarrow 1$
else if $L_{lte} \leq 0$ **then**
    $A \leftarrow 1$; $B \leftarrow L_{wifi} + (-1 \times L_{lte})$
else
    $A \leftarrow L_{lte}$; $B \leftarrow L_{wifi}$
end if
$ratio \leftarrow \frac{A}{B}$

B. Timeliness Model

In video coding, a video is typically represented as Group of Pictures (GoP) comprising of different types of frames, Intra-coded picture (I-frame), Predicted picture (P-frame), and Bidirectionally predicted picture (B-frame). I-frames are independent of any other frame, and each frame can be decoded into a single picture. Other frames like P and B are derived from their adjacent frames and I-frames. Typically loss of packets belonging to I-frames degrades the quality of video much more than if the loss had been of packets belonging to other frames. Since, if an I-frame is lost, then the subsequent P and B frames will become useless as they depend upon the I-frame for their decoding. Thus in the timeliness model, I-frames are given higher priority over

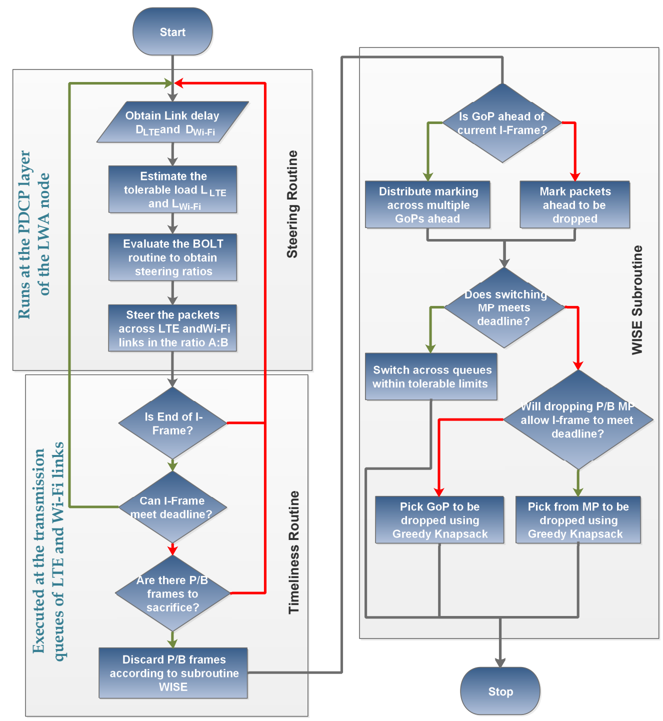


Figure 3: The flow chart of OASIS.

other packets by ensuring that they are delivered in time by sacrificing other frame packets. The model's working has been described in Figure 3. As soon as the last I-frame packet gets added in the transmission queue, the timeliness model scans the queue from the beginning for the packets that will miss the deadline. This estimation of packets missing the deadline is done based on the current queuing delay and propagation delay. If an I-frame packet misses the deadline, then we calculate the number of packets that must be dropped to make the I-frame packet meet its deadline. If the queue ahead of I-frame packet contains the required number of packets 1 for dropping, then the WISE subroutine is executed; otherwise, no change is made.

The WISE subroutine works as follows. It tries to optimally choose which packets to drop so that the quality degradation is minimal. In the WISE subroutine, if the packets ahead of the I-frame packets contain one or more GoPs then a distributed marking of packets is done across different GoPs ahead of current I-frame. Marking refers to the packets which can be dropped or switched to meet the deadline for current I-frame. For each GoP marking is done which could result in the same packet being marked more than once. These marked packets may also include I-frame packets if required. If there is no GoP ahead, then the required packets are simply marked. Now if by switching some of these marked packets on the other queue, if all the packets can meet their deadline, then they are switched to the other link's transmission queue. If they cannot be sent via the other link, then it is checked if the deadline can be met by just dropping the marked packets(MP). If I-frames need to be dropped even after dropping the MP then, entire GoPs are chosen from all the GoPs to be dropped using Greedy knapsack. If only MPs need to be dropped then, they are chosen using Greedy knapsack. For greedy knapsack I-frames are given the highest weight, P-frames are given intermediate weight, and B-frames are given the least weight. The knapsack is filled to have minimal weight.

IV. Performance Evaluation

A. Implementation Details

The topology is setup in NS-3 and is being used in emulation mode. This mode allows real-world applications to transmit packets to the simulated network. The setup is described in Figure 4. It comprises of the Server VM, the NS-3 Simulation running on the host OS, and the Client VM. The Server VM acts as the video streaming server. Here VLC media player is used to stream real-time videos to the client. The packets generated by the server pass through the simulated network topology in the NS-3 Simulation. These packets are further forwarded to the Client VM. This VM acts as a UE (smartphone) where the video is played out using VLC media player. The experimental parameters used in the simulation are described in Table II. These parameters are chosen to create a constrained environment where we can test and compare the different techniques. We expect that the observations made here will hold true even when we conduct experiments with more network resources and 802.11 ac. Also, we have set T (delay threshold) to be 150ms [11].

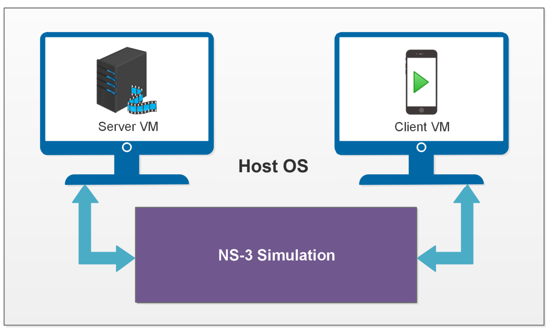


Figure 4: Experiment Setup.

Figure 1 explains the network topology for the LWA. There is only a single flow established between the UE and the live video streaming server. The UE is connected to both LTE and Wi-Fi. Packets arriving at the LWA node are split over both LTE and Wi-Fi based on BOLT. It is implemented at the LWA node. For setting up MPRTP two UDP flows are established with the UE from the live video streaming server. One flow is over LTE, and the other is over Wi-Fi. The packets are split on the different flows at the server. The splitting is done based on the throughput of each of the flows.

Table II: Experimental Parameters

Parameter	Value
LTE eNB bandwidth	5 MHz
Number of Resource Blocks	25
Tx power	20 dBm
Path Loss Model	Log Distance
Fading Model	Trace Fading Model
Scheduler	Proportional Fair
Wi-Fi Frequency, bandwidth	2.4 GHz, 20 MHz
Wi-Fi standard	IEEE 802.11 g
Wi-Fi Propagation Delay Model	Constant Speed
Wi-Fi Propagation Loss Model	Log Distance
Video Resolution	1280 $\times$ 720
Video Bitrate, Frames per second	1742 kbps, 25
Video Codec	H.264

1) Tagging I-frames: In our work I-frames are tagged at the server node in NS-3. The H.264 data in UDP packets is parsed to detect I-frames. A tag is attached to the packet which identifies the packet as belonging to I-frame. In the real world, I-frame packets can be tagged by the application by marking the IP packets. IP packets have unused bits in the type of service field which can be used for this purpose.

2) Reordering Problem: The Out-of-Order problem is prevalent when multiple paths are involved. The packets cannot be forwarded in the order they are received since this would result in a garbled and unrecognizable video. Thus to solve the problem the packets are scheduled for delivery to the application layer at a later time. The holding time is calculated as follows :

$$HoldingTime = T + SendingTime - ReceivingTime \quad (3)$$

Here, Sending time is the time at which the packet was sent from the server. Receiving time is the time at which the packet was received at the transport layer of the UE. Note that the total delay experienced by a packet including the holding time will never exceed T. If it does exceed T then the packet will be dropped since it has already missed its deadline and moreover it cannot be reordered without disturbing other packets. This reordering solution also works as a jitter buffer, since it removes the jitter and sends the packets to the receiver at the same rate with which they were streamed from the server. Thus the additional latency introduced by the jitter buffer at the client video player is minimized.

B. Experiment Scenarios

These scenarios test OASIS, LWA, MPRTP, LTE only, and Wi-Fi only techniques under different network conditions.

1) Scenario #1: This scenario tests the techniques when the UE is mobile in an indoor environment. The UE is made to oscillate rapidly between the eNB and the Wi-Fi AP. Thus the following cases can be observed, when one of the links is better than the other (*i.e.,* when the UE is closer to one Radio Access Technology (RAT) and farther than the other) and when both the links are bad (*i.e.,* when the UE is equidistance from both the RATs).

2) Scenario #2: This scenario tests the techniques under the variable background traffic present on the wireless medium. Seven background nodes are added on both the Wi-Fi and the LTE links. Each of the nodes has a UDP flow established with a data rate of 1 Mbps. The traffic is variable on both the links, *i.e.,* it alternates between an on-state and an off-state. Thus the following cases can be observed, when there is heavy background traffic on both the links (*i.e.,* when the background traffic for both the links is on) and when there is heavy traffic on one and low traffic on the other link (*i.e.,*

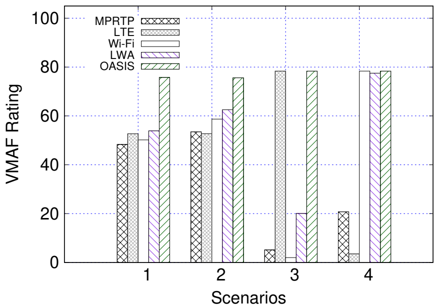


Figure 5: VMAF Ratings Comparison for all the scenarios.

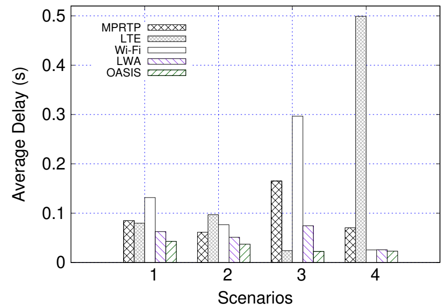


Figure 6: Average Delay Comparison for all the scenarios.

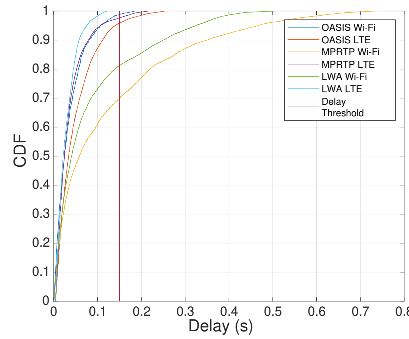


Figure 7: CDF of Delay in Scenario #1.

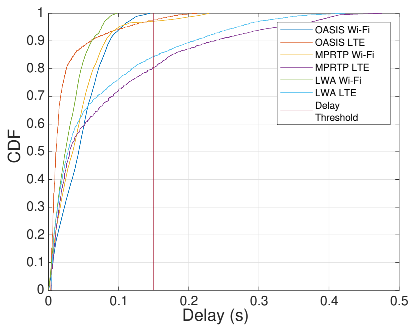


Figure 8: CDF of Delay in Scenario #2.

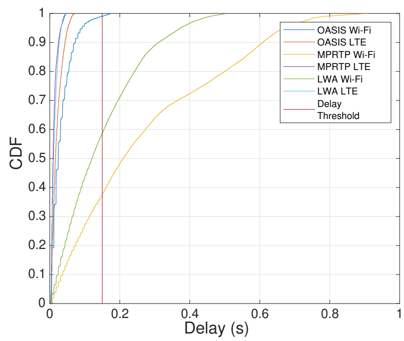


Figure 9: CDF of Delay in Scenario #3.

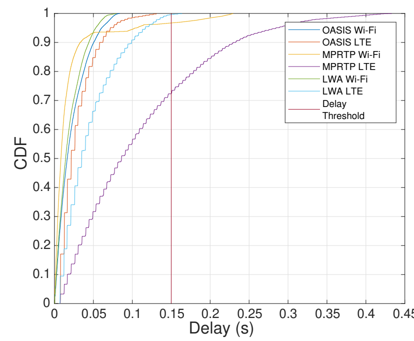
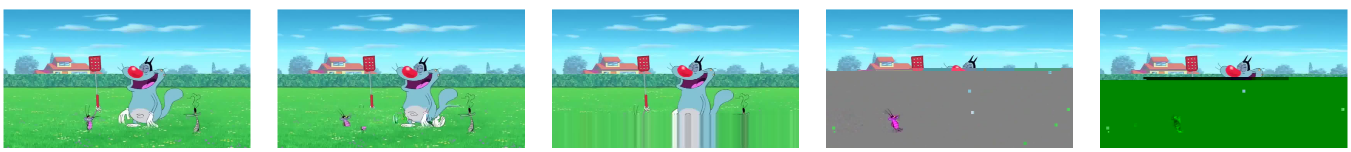


Figure 10: CDF of Delay in Scenario #4.



(a) OASIS **(b)** LWA **(c)** MPRTP **(d)** LTE only **(e)** Wi-Fi only

Figure 11: Snapshot of an H.264 video frame observed under Scenario #2.

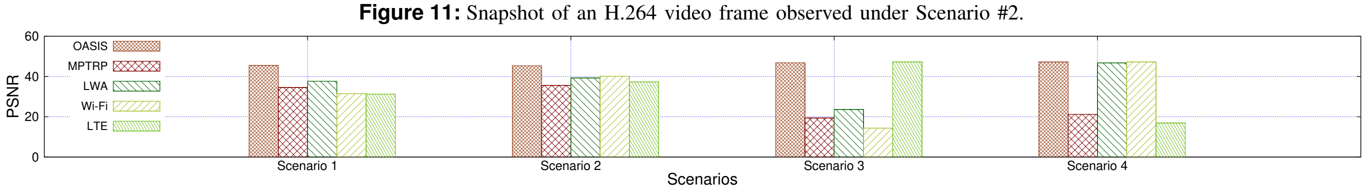


Figure 12: PSNR observed in different Scenarios.

when the background traffic for one link is on, and the other is off). The scenario where there is no traffic on both the links is not considered since it is a trivial case.

3) Scenario #3: This scenario tests the techniques if only the LTE link is capable of meeting the low latency requirement and the Wi-Fi link is unusable *i.e.,* it is a high latency link (latency $\geq$ 1 sec).

4) Scenario #4: This scenario tests the techniques if only the Wi-Fi link is capable of meeting the low latency requirement and the LTE link is unusable *i.e.,* it has high latency.

C. Experiment Results

Here we are comparing the live video streaming performance of LTE only, Wi-Fi only, LWA, MPRTP, and OASIS by streaming a 720p video whose details are specified in Table II. The video with the given specifications is chosen since it works well in our constrained environment and is able to demonstrate the performance difference in all the techniques. Video Multimethod Assessment Fusion (VMAF) scores and Peak Signal To Ratio (PSNR) values are used to evaluate the quality of live video streaming over the different techniques [12]. The average packet delay experienced by each technique over all the four scenarios is recorded to show which techniques meet the low latency requirement. The cumulative distribution function (CDF) of the per-packet delay experienced on both the LTE and the Wi-Fi link for the multipath techniques shows the number of packets experiencing delay below the threshold.

1) Performance comparison in Scenario #1: The VMAF ratings as shown in Figure 5 and the PSNR per frame as shown in Figure 12 show that OASIS outperforms all the other techniques in this scenario. For LTE only and Wi-Fi only, each link is only usable when the UE is closer to its respective RAT. The latency increases as the UE moves away from the RAT, thereby degrading the performance. For LWA, Figure 7 shows that many packets miss the deadline on the Wi-Fi link since more traffic has been directed towards it. LWA favours Wi-Fi because the RTT reported is usually less for Wi-Fi than LTE. For MPRTP, it splits the traffic on each link based on the throughput reported by the UE. By the time the throughput is reported, the wireless conditions have already changed. Thus MPRTP incorrectly steers the traffic as seen in Figure 7. For OASIS, Figure 7 shows that it correctly steers the traffic with a very small number of packets missing the deadline. It adapts quickly to the rapidly changing wireless medium.

Table III: Improvement after applying the Timeliness Model

	Before Timeliness Model	After Timeliness Model
Total Lost Packets	62	56
I-Frame Packets Lost	60	12
VMAF Rating	68.057	75.43

2) Performance comparison in Scenario #2: The VMAF ratings as shown in Figure 5 and the PSNR values as shown in Figure 12 show that OASIS outperforms all the other techniques in this scenario. For LTE only and Wi-Fi only, the latency on each link increases in the presence of heavy background traffic, thereby decreasing the performance. For LWA, Figure 8 shows that it puts on more load on LTE than it could handle, resulting in packets missing the deadline. This is because the RTT reported by ICMP packets is unable to capture the actual network conditions. Still, it performs better than LTE only, Wi-Fi only, and MPRTP. For MPRTP, Figure 8 shows that it puts on more load on LTE than it could handle. This is because it splits the traffic based on throughput observed and does not account for latency. Also, it reacts slowly when the traffic pattern changes. For OASIS, Figure 8 shows that only a small fraction of packets miss the deadline. This is because it steers traffic towards the link with the lower traffic when higher traffic is present on the other.

3) Performance comparison in Scenario #3: The VMAF ratings as shown in Figure 5 and the PSNR values as shown in Figure 12 show that OASIS and LTE perform similarly while outperforming all the other techniques in this scenario. For LTE, the scenario is set up to have very low latency on this link. This is shown in Figure 6. For Wi-Fi, the scenario is set up to have very high latency on this link. This is shown in Figure 6. For LWA, since the RTT reported by ICMP packets is lower for Wi-Fi than LTE, hence more traffic is steered through Wi-Fi than LTE. Thus resulting in performance degradation as evident in Figure 9. For MPRTP, Figure 9 shows that it incorrectly steers more traffic to the Wi-Fi link. This is because it steers traffic based on throughput and not based on latency. For OASIS, Figure 9 shows that it utilizes both the links optimally by steering maximum traffic through the LTE link.

4) Performance comparison in Scenario #4: The VMAF ratings as shown in Figure 5 and the PSNR values as shown in Figure 12 show that OASIS, LWA, and Wi-Fi perform similarly while outperforming all the other techniques in this scenario. For LTE, the scenario is set up to have very high latency on this link. This is shown in Figure 6. For Wi-Fi, the scenario is set up so to have very low latency on this link. This is shown in Figure 6. For LWA, since the RTT reported by ICMP packets is lower for Wi-Fi than LTE, hence more traffic is steered through Wi-Fi than LTE. Thus resulting in improved performance as evident in Figure 10. For MPRTP, Figure 10 shows that it incorrectly steers more traffic to the LTE link. It is unable to identify when to use a single link. This is because it steers traffic based on throughput and not based on latency. For OASIS, Figure 10 shows that it utilizes both the links optimally by steering maximum traffic through the Wi-Fi link.

5) Performance of the Timeliness Model: Table III shows the performance improvement after applying the timeliness model to BOLT in Scenario #1. An improvement of 7% in the VMAF rating is observed after applying the model. In other scenarios BOLT without timeliness model hardly has any packet losses. Thus applying the timeliness model does not have much effect.

V. Conclusions

This work presented the OASIS framework for streaming live video over LWA. The steering algorithm of OASIS, BOLT, aggregated the links effectively, and it could be concluded from the results that OASIS outperformed MPRTP and LWA. This was because BOLT precisely predicted the load accommodable on each link before the threshold was attained. Also, the steering was done at the LWA node as opposed to at the server, which enabled the solution to react faster to the rapid changes in the wireless channel. The results also revealed that the timeliness model of OASIS, which prioritized packets of I-frame over other frames, reduced the drop in the quality. Thus OASIS successfully enhanced the live video streaming over LWA by 1.4$\times$ as compared to MPRTP.

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