A Path-Aware Scheduler for Air-to-Ground Multipath Multimedia Delivery in Real Time

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A Path-Aware Scheduler for Air-to-Ground Multipath Multimedia Delivery in Real Time

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Abstract—The use of multipath techniques in transmission has emerged in the last years thanks to their potential in increasing throughput. They can also be used as a means to counteract errors or losses in transmission, thus increasing reliability. In this work, we focus on the challenging scenario of real-time video streaming from an Unmanned Aerial Vehicle (UAV) via multiple wireless channels. We propose a lightweight scheduler capable of dynamically selecting the paths to be used and of determining the necessary redundancy rate to protect the multimedia flow. Our scheduler, implemented as a module of the GStreamer framework, can be used in real or simulated settings. The results we present show that the proposed scheduler can be used to target a very low loss rate by dynamically adapt to varying channel conditions in terms of losses and experienced delay.

Index Terms—Scheduling, Redundancy, Multipath, UAV, RTP

1 Introduction

The use of multipath techniques has emerged as one of the key strategies to improve channel reliability and availability in multimedia transmission, especially on wireless networks. multipath transmission is a technique leveraging network diversity, in which the same traffic is shared or replicated over multiple channels. In this way, data lost on a physical link may be recovered on other one. The more uncorrelated the channels are, the more efficient such an approach can prove to be. multipath delivery has several advantages: *(i)* it can improve channel availability and reliability, *(ii)* it can increase the throughput or choose the lowest-delay path, and *(iii)* it allows for path aggregation and load balancing. Consequently, it has the potential to improve both Quality of Service (QoS) and user-perceived Quality of Experience (QoE) in real-time multimedia applications. UAVs can largely benefit from the use of multipath transmission, especially when operated over unreliable wireless networks, in the absence of Line of Sight (LoS) or remotely [1]. A critical aspect in multipath transmission is the packet scheduling. A multipath scheduler must perform three main tasks: *(i)* path selection, *(ii)* packet selection, and *(iii)* packet protection [2]. This implies that a multipath scheduler needs full or partial Channel State Information (CSI) of the used links to determine whether and when using a given channel, and the share of the data stream to be allocated to each channel. multipath packet scheduling is challenging in wireless networks because of the heterogeneity and time-variability of the paths, in terms of the available bandwidth, delay, cost, and congestion level. Furthermore, real-time multimedia applications typically use protocol stacks with no delivery guarantee, packet protection or congestion control. A reference stack is provided by the use of the Real-time Transport Protocol (RTP) over User Datagram Protocol (UDP).

In this article, we propose Path-Aware Dynamic multipath schEduler (PADME), implementing a scheduling strategy inspired to an interleaved weighted Round Robin (RB) mechanism operating on *(i)* path selection, and *(ii)* data protection through replicas. Looking at Figure 1, which depicts our reference sce-

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nario, an UAV transmits a multimedia stream towards a Ground Control Station (GCS) via three wireless channels. The PADME scheduler, relying on a RTP/UDP protocol stack, selects the channels to be used - all three in Figure 1 - and the necessary redundancy rate - e.g., packet 5 is replicated 2 times, packet 3 has no replicas - to increase the probability of correctly receiving all packets at destination. We underline how a multipath system can tolerate the temporary unavailability of e.g., one channel because the remaining available ones can be used for data delivery, a critical condition that Forward Error Correction (FEC) or other data protection mechanisms cannot provide. PADME performs both path selection and channel allocations depending on CSI, such as the Packet Loss Rate (PLR), which is periodically reported by the receiver by means of the Real-time Transport Control Protocol (RTCP). The choice of using PLR as scheduling criterion in PADME is motivated by the fact that it is a function of the channel interference, depending on congestion, latency, delay jitter, and buffer overflow, among others. PADME weights the use of each channel according to its Receiver Report (RR). Intuitively, the higher the experienced PLR, the lower the number of packet allocated to a channel in the next transmission round. PADME has been designed as a lightweight solution in terms of computational requirements, making it suitable for constrained devices that are often used as payloads onboard UAVs. In this work, we take as reference scenarios in which real-time and quasi-real-time video feeds are collected from UAVs and sent to a fixed GCS via multiple wireless channels. We assume the channels to be subject to interference due to e.g., obstacles, congestion or other phenomena that can cause packets to be lost. PADME can counteract such phenomena to increase the probability of a good-quality video feed at the receiver.

The rest of the paper is organized as follows: we first survey multipath schedulers in the literature in Section 2, focusing on their advantages and limitations. Then, we present the functionalities of PADME in Section 3, and the simulation setup and results in Section 4. The conclusions are in Section 5.

2 Path-aware Scheduling in Multipath Systems

In this section, we survey state-of-the-art multipath schedulers and packet protection techniques. Scheduling means selecting the channel on which packets are to be transmitted. Packet protection is related to protecting packets against errors so that the receiver can correctly decode the message. In a multipath system, multiple links are jointly used; because of it, dynamically determining the subset that can meet predefined constraints is not trivial. It may require, among other factors, full or partial knowledge of CSI through e.g., the use of feedback loops. Similarly, estimating the redundancy rate in an online fashion can be challenging, causing waste of resources in the case of a too high rate [1], or information loss in the case of a not sufficient one [3]. There is a trade-off between protection and bandwidth saving. Unfortunately, most of the state-of-the art schedulers concentrate on one aspect while neglecting the other. For example, the legacy RB scheduling strategy [4] sends data via the available paths in a sequential manner neglecting path heterogeneity [2]. This translates into, for instance, slow channels being overloaded and fast channels being underutilised [5]. Experiments have revealed that RB exhibits a poor performance level when used in conjunction with the multipath Transmission Control Protocol (MP-TCP) [6]. MP-TCP must be considered as one of the first successful attempts at using multipath protocols in real settings, opening the way to other multipath variants, such as MP-RTP [7], MP-QUIC [8], and MP-DASH [9]. Another conventional scheduler is the Weighted Round Robin (WRR) one, which is an improved RB scheduler scheduling packets according to statistical weights assigned to each channel. A limitation of WRR is that the weight assigned to a path is typically static, making it impractical for time-varying channels, especially fast ones. Other schedulers, like the Deficit Round Robin (DRR), the Weighted Fair Queuing (WRQ), and the Strict

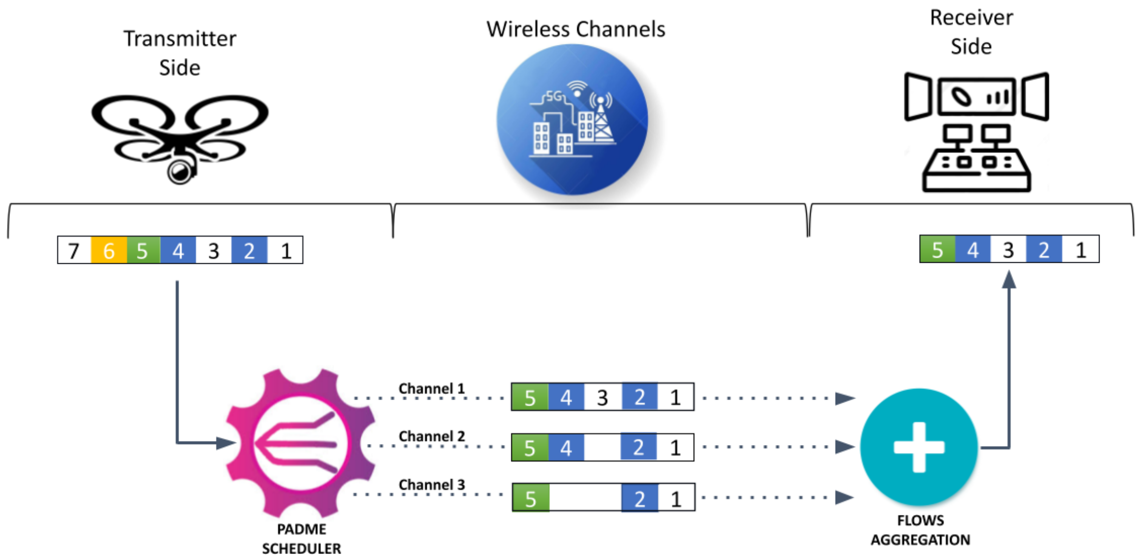

Fig. 1: A multimedia stream of packets is sent from a UAV to a GCS via multiple channels through PADME scheduler, selecting the channels to be used and the necessary redundancy rate.

Priority [6] ones suffer from similar limitations, i.e., poor adaptability.

Path-Aware Networking (PAN) strategies are emerging as approaches taking into consideration the channel (or path) characteristics, making them available to endpoints as information to be leveraged to select proper paths for transmitted data flows. Being able to exploit disjoint network paths can provide, according to the Path Aware Networking Research Group (PANRG), failure resilience and can open to optimization algorithms, among others. PAN strategies have shown advantages over the traditional vision of Internet as a *simple pipe connecting two endpoints* because of the emphasis on path diversity, among other factors [10]. Channel characteristics of interest for path forwarding strategies include Round-Trip Time (RTT), PLR, throughput, and available bandwidth [5]. An example of path-aware scheduler is the Round Trip Time Threshold Scheduler[1], which selects the first available path with smoothed RTT below a certain threshold. Another example is the Lowest RTT First scheduler, which provides low latency for short flows or a throughput increase for long flows, in both cases by selecting the path exhibiting the lowest RTT. Studies in [11], [12], [13], [14] have shown that scheduling strategies that use RTT or delay as main (or only) metrics for path selection are capable of decreasing the probability of packets arriving after expiry time, which would cause them to be considered as lost. Anyway, those schedulers may suffer from the so-called *head-of-line blocking* phenomenon, occurring when paths are strongly heterogeneous in terms of latency, causing faster paths to be underutilised [6] in a FIFO setting because of slower ones taking too long to send out packets. Other path-aware scheduling strategies rely on PLR [3], [14], considering as lost (*i*) the packets not actually arriving to destination, (*ii*) those unrecoverable because of errors, and (*iii*) those arriving after expiry time [5]. In this regard, the use of multiple paths provides diversity in the sense that packets lost on one path can be recovered on other ones; a packet is considered lost only when it cannot be recovered from any of the paths.

As far as packet protection is concerned, several techniques are well established, such as the use of FEC or of Automatic Repeat reQuest (ARQ). The former adds redundancy to the transmission at the expense of used bandwidth; the latter retransmits lost packets to increase the probability of a correct delivery, but increasing

1. Details at https://tools.ietf.org/id/draft-bonaventure-iccrg-schedulers-01.html.

the congestion probability and sacrificing bandwidth [2]. ARQ is typically excluded - at least at transport layer - in the case of real-time multimedia transmissions because retransmissions are not useful if not detrimental [15], while FEC is often used although its impact on computational resources that can be not negligible on resource-constrained devices.

The scheduler we propose in this work, namely PADME, dynamically adapts to varying channel conditions leveraging a feedback loop to collect CSI. PADME exploits data in the periodic RR to select the paths to be used in the next time period (or cycle, as we present in Section 2) by means of dynamic channel weights, and estimates the needed redundancy rate that is needed to counteract the average loss rate in the previous periods. In order to have a simple, efficient, and very lightweight implementation, PADME makes use of a repetition code. Replicas of the same packet can be sent on different paths to increase the probability of a correct delivery, avoiding any delay due to retransmissions or coding/decoding operations. Recalling that our reference scenario is real-time multimedia delivery, we underline how this approach is advantageous in terms of delay because the expiry time of sent packets is strictly limited. PADME has been implemented as a module of the GStreamer open source multimedia framework, and is fully presented in the next section.

3 Design and Functionality

In this section, we present PADME and its inner mechanisms, which are redundancy estimation, scheduling class selection, channel weight optimization, and channel interleaving strategy.

Redundancy Estimation and Scheduling Class Selection

We consider a multipath transmission system with three channels $c1, c2, c3$ in what follows. Anyway, note that PADME can be used in any configuration with at least two channels.

We define a RB *cycle* as the time period in which N information packets are sent. In fact, a cycle is divided into K *rounds*, such that, in each round, one out of the K information packets and its replicas (if needed) are transmitted. Then, we define seven *scheduling classes* from A to G as shown in the first column of Table 1. A scheduling class is defined by a vector $\boldsymbol{r} = [r_1, r_2, r_3]$ (in the case of three available channels) of redundancy ratios r_i, which are the rates for sending i replicas of an information packet via i different channels in a round. The average redundancy factor $\overline{f}$ determines the average number of packet replicas per round (see Table 1). Hence, we obtain $N = \overline{f}\,K$ as the total number of packets that are transmitted per cycle, with $R = N - K$ being the number of redundancy packets per cycle. A the end of each cycle, a new class can be selected depending on the reported PLR. For a lowering PLR, the class used in the next cycle will be chosen to lower $\overline{f}$, and vice versa. Thus, PADME is an event-driven scheduler, triggered at the reception of a RR, which forces the scheduling class to be changed if needed. In fact, a RR is received every τ seconds, providing a PLR value per c_i and the aggregated End-to-End (E2E)-PLR. The latter is used to guide the selection of a different scheduling class if needed, targeting a predefined global threshold PLR_{th}. The rationale is in selecting a class with minimal overhead but with enough redundancy to increase the probability of a correct data delivery.

For the sake of clarity, we provide some examples, assuming $K = 100$. Looking at Table 1, let G be the scheduling class selected for the next cycle. Then, the packet redundancy ratios to be used are $\boldsymbol{r}$ = [0, 0, 1]. The average redundancy factor $\overline{f} = 0 \cdot 1 + 0 \cdot 2 + 1 \cdot 3 = 3$, providing $N = \overline{f}\,K = 3 \cdot 100 = 300$. In class G, $\overline{f} = 3$ replicas per information packet are sent per round. If class F is selected, then $\boldsymbol{r}$ = [0, 0.5, 0.5] as shown in Table 1: half of the information packets of the cycle are transmitted with 3 replicas, and the other half with 2 replicas. Therefore, channel interleaving goes as follows: in the first round, 3 channels c_1, c_2, c_3 are used to transmit 3 replicas of the first packet; in the second round, 2 channels c_1, c_2 are used; in the third round, 3 channels c_3, c_1, c_2 are used, and so on. This pattern $3, 2, 3, 2...$ continues for the whole cycle until all the N packets have been transmitted. A similar channel interleaving procedure is used

Scheduling class	Redundancy ratios $[r_1, r_2, r_3]$			$\overline{f}$	Channel Interleaving: The first four rounds of a cycle							
					Round 1		Round 2		Round 3		Round 4	
					Reps	Channels	Reps	Channels	Reps	Channels	Reps	Channels
G	0	0	1	3	3	$c_1c_2c_3$	3	$c_1c_2c_3$	3	$c_1c_2c_3$	3	$c_1c_2c_3$
F	0	0.5	0.5	2.5	3	$c_1c_2c_3$	2	c_1c_2	3	$c_3c_2c_1$	2	c_3c_1
E	0	0.75	0.25	2.25	3	$c_1c_2c_3$	2	c_1c_2	2	c_3c_1	3	$c_2c_3c_1$
D	0	1	0	2	2	c_1c_2	2	c_3c_1	2	c_2c_3	2	c_1c_2
C	0.25	0.75	0	1.75	2	c_1c_2	2	c_3c_1	1	c_2	2	c_3c_1
B	0.25	0.25	0	1.25	2	c_1c_2	1	c_3	1	c_1	2	c_2c_3
A	1	0	0	1	1	c_1	1	c_2	1	c_3	1	c_1

TABLE 1: PADME mechanisms: (left) the scheduling classes with redundancy ratios r_i; (right) the interleaving policy, showing the channels rotation in the first 4 rounds.

for any scheduling class selected.

Channel Weight Optimization

We define the channel weight w_i as the number of packets to be transmitted via c_i in the next cycle. Each packet may be replicated on other channels. In order to determine how much each path should be used to minimise the E2E-PLR, we solve an optimization problem based on the Sequential Least SQuares Programming (SLSQP) minimization algorithm. The objective function to be minimised is the Euclidean's distance between the vector of the weights (to be determined) and a target vector whose components are the inverse of the PLR reported in the previous cycle per channel. The aim is in limiting as much as possible the use of channels that have reported the highest PLR. The vector of the weights is defined as $w = [w_1, w_2, w_3]$, with w_i ranging between $w_i^{min} \leq w_i \leq K$, where w_i^{min} is the minimum number of packets per cycle used for probing a channel, i.e., to collect enough samples to roughly estimate its PLR.

Channel Interleaving Scheme

Summarising, the interleaving of the channels is determined by the redundancy ratios of the selected class and by the weight allocated to each channel. Each transmission of an information packet on a channel decreases the residual weight of the channel; once its weight reaches zero, a channel cannot be used anymore until the next cycle. Packets are transmitted in rounds, meaning that an information packet and its replicas (if needed) are transmitted in a round. The number of channels to be used per round depends on the redundancy ratio of the current scheduling class.

4 PROOF OF CONCEPT & EVALUATION

Simulation results are presented in this section to evaluate the performance level of PADME. The reference scenario is a multipath multimedia delivery from UAVs to GCSs in real time. The Proof of Concept (PoC) simulator is built leveraging Gstreamer and its modular plugins. The sender-side part of our PoC runs on a constrained device - a Raspberry Pi (RPi) in our case - sending data to a desktop machine running Ubuntu. A GStreamer pipeline, i.e., a sequence of GStreamer plugins designed to handle media, has been set up, and we customised the RB plugin to implement PADME. Each time a RR is received, an external Python routine is launched to select the scheduling class to be used in the next cycle. We underline how a dejitter buffer is used at the end of the GStreamer pipeline, reordering packets, removing duplicates, and dropping packets arrived after expiry time $exp_t = 200$ [ms]. The aim of our analysis is in assessing if PADME can track the target PLR_{th} by dynamically selecting the most proper scheduling class at each new cycle. PLR has values $1\%, 2\%, 3\%$ in our tests, and PLR_{th} is set to 0.5%. We assume $K = 100$ packets, $w_i^{min} = 10$, the RR interval equal to 3s, and the delay applied to ch_3 to range within (*i*) $100 - 150$ [ms] (less than exp_t) or (*ii*) within $150 - 400$ [ms] (greater than exp_t for some packets).

4.1 Tracking the target PLR

Figure 2 shows the E2E-PLR when a PLR is applied per channel as detailed in the legend. It shows that PADME is able to track the target, $PLR_{th} = 0.5\%$, by selecting the most appropriate scheduling class at each cycle. For enhanced clarity, Figure 2 also shows the E2E-PLR when class A only (one channel) or class G only (three channels) is in use in order to present the range within which PADME can operate in our simulations.

4.2 Used scheduling class and impact of delay

The scheduling class selected by PADME to track PLR_{th} can be seen in Figure 3, showing how PADME typically oscillates within two contiguous classes after an initial transient time. To ease the reader, we also plot the average redundancy rate in Figure 3: if the average PLR is higher (e.g., 3%), then the average redundancy rate is also higher, and vice versa. Figure 3 also shows the impact of a channel one-way delay greater than exp_t: if a packet arrives after expiry time, it is discarded by the dejitter buffer, thus counting as a loss. Because of this, PADME slightly increases the average redundancy rate to target PLR_{th} also in this case.

5 Conclusions

In this work, we proposed PADME, a lightweight and dynamic scheduler for multipath systems designed to deliver real-time multimedia flows from an UAV to a GCS. PADME operates by dynamically selecting the channels to be used in transmission and using packets replicas to counteract packet losses. The number of replicas to be sent is periodically estimated by using a feedback loop reporting the PLR experienced in the previous period. PADME is built upon the GStreamer framework and can be used in real or simulated settings. The results we provide in this work show that PADME is able to target a PLR threshold, which can be customised. Thus, in the presence of a varying PLR, as common with time-varying wireless channels, PADME tailors the number of channels to be used and the necessary redundancy rate to the instantaneous conditions. In challenging conditions, a multipath setup may represent the only solution able to increase the probability of a correct and real-time multimedia delivery, even tolerating the temporary unavailability of a channel pertaining to the pool in use.

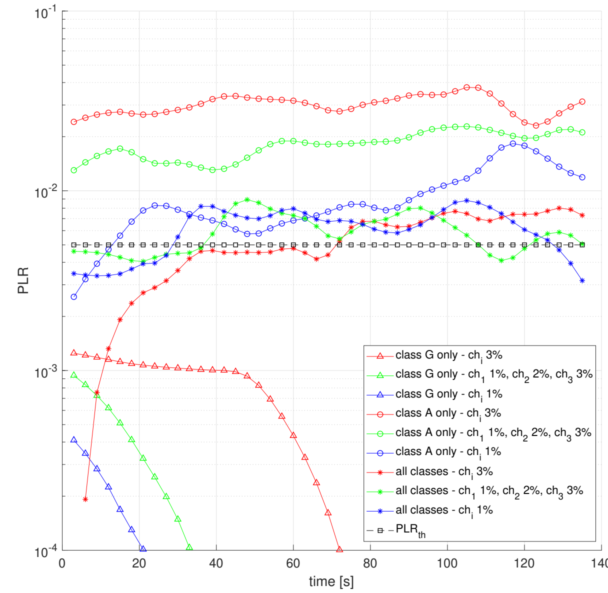

Fig. 2: E2E-PLR: (*i*) with one channel (class A), (*ii*) with three channel (class G), (*iii*) with PADME (all classes). The target is $PLR_{th} = 0.5\%$, all packets arrive before exp_t.

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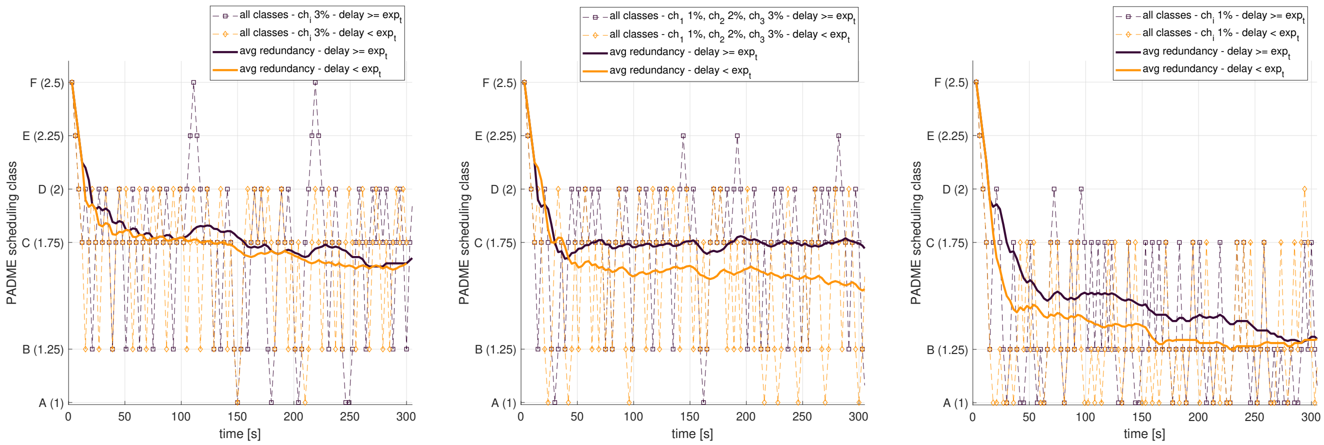

Fig. 3: Scheduling classes in use by PADME and resulting average redundancy ratios in the presence of a varying PLR and of a delay larger than exp_t for ch_3 (in blue).

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