An Adaptive Flow-Aware Packet Scheduling Algorithm for Multipath Tunnelling

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Abstract—This paper proposes AFMT, a packet scheduling algorithm to achieve adaptive flow-aware multipath tunnelling. AFMT has two unique properties. Firstly, it implements robust adaptive traffic splitting for the subtunnels. Secondly, it detects and schedules bursts of packets cohesively, a scheme that already enabled traffic splitting for load balancing with little to no packet reordering.

Several NS-3 experiments over different network topologies show that AFMT successfully deals with changing path characteristics due to background traffic while increasing throughput and reliability.

I. INTRODUCTION

Network paths can be unreliable and slow [12], [5]. Redundancy is an obvious solution for this issue. Redundancy has been used to provide reliability and higher throughput in many fields of computer engineering, e.g. databases, storage, power supply, but seldomly for network paths. There are several proposed concepts for redundancy: Multipath TCP [6] and Multipath Tunnelling [3].

Multipath TCP (MPTCP) grants more reliability, but needs every client and every server to have direct full access to all network uplinks (figure 1) [6]. This complicates wiring. Additionally, it needs all clients to implement MPTCP, a complex protocol. It also does not solve the problem for UDP flows. So while MPTCP performs better than load balancing, it still leaves a lot of issues unaddressed.

Multipath Tunnelling (MT) addresses these issues. As visible in figure 2, only the tunnel endpoints $T_{entry}$ and $T_{exit}$ need to see and understand the sub-tunnels. The clients and servers don’t know they’re connected by multiple paths, they need no additional wiring or implementation of a new network protocol. Since all flows between the two networks are tunneled, this also works for UDP. Lastly, all current prototypes and their concepts are less complex than the Multipath TCP concept and its implementations [9].

Our novel contributions include: We introduce AFMT, a packet scheduling algorithm for adaptive flow-aware multipath tunnelling. AFMT aims to overcome the throughput, reordering and adaptivity issues of existing MT approaches. We evaluate AFMT for diverse networks with changing path characteristics. This shows that AFMT improves reliability and throughput compared to a classic packet scheduling scheme. The evaluation in this paper focuses on wired connections, nevertheless AFMT research focuses on providing a general solution.

II. BACKGROUND

TCP is sensitive to packet reordering [4], it interprets reordering as a sign of packet loss and reacts with spurious retransmits and throughput reduction. TCP uses a sliding window (congestion window, cwnd) algorithm to adjust its send rate to the path’s capacity [11]. Often, TCP sends the contents of a cwnd as one burst or flowlet [7]. The set of all transmitted packets in a transport layer association is defined as a flow [12]. As illustrated in figure 3, it is possible to utilise flowlets to achieve traffic splitting with little to no packet reordering.

Multipath tunnelling is known to induce heavy packet reordering [3]. This research proposes to reduce it by using flowlet switching [7], a scheme that reduced packet reordering for a similar problem (ISP load balancing) to very little to no occurrence.

In multipath routing context, packet scheduling refers to the task of choosing an output queue for every packet from an input queue [10]. In a MT system one output queue maps to one subtunnel. The behaviour of the packet scheduling algorithm is central to the behaviour of the whole MT system [5].
III. AFMT

AFMT is built on the assumption that using these results gives comparable or even better results than inventing an own path estimation scheme. DCCP and TCP maintain an estimation of the path’s RTT and capacity for their congestion control. Decades of research have been invested to optimise these [12], [8]. The following subsections describe the realisation of flow awareness and adaptivity.

A. Flow-Awareness

To find the applicable subtunnels and match the flow of a packet, a central data structure that tracks all flows is necessary. Therefore AFMT uses a flow table with the flow_id as key and a tuple of last subtunnel and timestamp as value. For every flow id it returns the last subtunnel used by this flow and a timestamp. This timestamp indicates the absolute time when the last packet of our flow was sent through the associated subtunnel.

With this data AFMT can determine the applicable subtunnels as shown in Algorithm 1. Relevant entities are the subtunnels $s_i$, the to-schedule packet $p$ and the absolute timepoints $t_i$. Initially AFMT obtains the flow-id of $p$, $p$ is finally sent via $s_i$. It can be obtained from the operating system. Every operating system that supports network address translation (NAT) needs to track flows and can (more or less directly) provide flow-ids. For Linux this is possible relatively simple with the `conntrack` netfilter module. In most use cases AFMT targets, $T_{exit}$ is the internet gateway of a organisation’s local network, a device that already implements NAT. Therefore there’s no overhead for flow identification and tracking necessary.

Next we lookup the flow id in the flow table (Line 6). If it exists we assign the data to two local variables (Line 7), and calculate $\delta$ the time that has passed since the last packet of our flow was sent.

Then the smoothed round trip time (SRTT) of a subtunnel is obtained from the transport protocol implementation[4] It’s more resistant to fluctuations and therefore a more meaningful proposition about the path than the RTT[11].

Knowing $s_i$.SRTT, the SRTT of a subtunnel $i$ it is possible to predict when $p$ will arrive at $T_{exit}$, namely in $s_i$.SRTT time from now and $s_i$.SRTT + $\delta$ time from when $p_{last}$ was sent. Comparatively $s_{last}$.SRTT gives the arrival time of $p_{last}$ from when it was sent. Therefore if $s_i$.SRTT + $\delta$ is larger than $s_{last}$.SRTT $p$ will arrive after $p_{last}$ and we can add $s_i$ to the list of applicable subtunnels (Lines 11-12). This is done for all subtunnels other then $s_{last}$.

After acquiring the list of applicable subtunnels AFMT selects the best of them ($s_{opt}$) adaptivity wise, which is explained in more detail in the next subsection (Line 15). Then the flow table is updated with the new values of $s_{opt}$ and the current time $t_{now}$ and $p$ is finally sent via $s_{opt}$ (Lines 16-17).

If $p$.flow_id is not found in the flow table i.e. it starts a new flow, AFMT directly calls the adaptive selection process with all available subtunnels $s_1, ..., s_n$ to determine $s_{opt}$ (Line 19). Then, as previously we update the flow table and send $p$ via $s_{opt}$ (Line 20-21).

Algorithm 1: AFMT: Flow-Awareness

1   Input_Table $q$
2   Subtunnels $s_1, ..., s_n$
3   $p \leftarrow q$.dequeue()
4   if defined(flow_table$[p$.flow_id]) then
5       $(s_{last}, t_{last}) \leftarrow$ flow_table$[p$.flow_id]
6       $\delta = t_{now} - t_{last}$
7       $s_{applicable} \leftarrow s_{last}$
8       for $s_i$ in other_subtunnels do
9           if $s_i$.SRTT + $\delta > s_{last}$.SRTT then
10              $s_{applicable}.append(s_i)$
11       end
12       $s_{opt} \leftarrow select_adaptively(s_{applicable})$
13       flow_table$[p$.flow_id] $\leftarrow \{s_{opt}, t_{now}\}$
14       $s_{opt}.send(p)$
15   else
16       $s_{opt} \leftarrow select_adaptively(s_1, ..., s_n)$
17       flow_table$[p$.flow_id] $\leftarrow \{s_{opt}, t_{now}\}$
18       $s_{opt}.send(p)$
19   end

B. Adaptivity

Algorithm 2 illustrates how the best subtunnel adaptivity wise is chosen. Line 1 iterates over all $s_i$ and calculates the weighted fill for each. Then, the subtunnel with the lowest one is selected. weighted fill aims to model the current load

1For Linux it is possible to get these values via getsockopt().
of the subtunnel. It considers the fill of the buffer associated with $s_i$: $s_i.f\_fill$. $s_i.f\_fill$ is added to the size of $p$ to get the full load this subtunnel would have to shoulder. This value is divided by a value comparable to the "bandwidth-delay-quotient": $s_i.cwnd/s_i.SRTT$.

Algorithm 2: AFMT: Adaptivity (select_adaptively())

1. \( s_{\text{opt}} \leftarrow s_i \text{ with minimal } s_i.\text{weighted\_fill} \) where
2. \( s_i.\text{weighted\_fill} = \frac{s_i.f\_fill+p.\text{size}}{s_i.cwnd/s_i.SRTT} \)
3. \( = \frac{s_i.f\_fill+p.\text{size}}{s_i.cwnd} \cdot s_i.\text{SRTT} \)

IV. Evaluation

To evaluate AFMT, it was implemented in NS-3 and used with several network topologies and multiple payload flows.

A. NS-3 and The Network

For modelling wired links, NS-3 provides a PointToPoint and a CSMA model. We chose the CSMA model for all links since it provides the closest model of the Ethernet and DSL links of a typical application case [1]. All CSMA net device queues are configured as drop tail queues.

Data Rates of 16, 32 and 50 Mbit/s were chosen to model a fast cable internet connection and two slower DSL subscriber lines. We also conducted a second set of experiments with only two uplinks, modelling a 32 and a 50 Mbit/s line. Intermediate Routers between \( T_{\text{entry}} \) and \( T_{\text{exit}} \) were introduced to partially model the IP Layer routing overhead and different backbone paths of a real client to online server path. All links in the backbone network are modelled with 1 GBit/s. The same goes for the CSMA link from \( T_{\text{exit}} \) to the server, which represents a connection in a data center. The local network configuration of the clients models a local gigabit Ethernet link. As a baseline we also evaluated how the three payload flows perform if they are routed single path via the fastest 50 Mbit/s link without any tunneling or multipath aggregation.

For the CSMAChannel delay which models the propagation delay between two nodes including all switches and hubs, we chose 6500ns. Considering an average switch overhead of 600ns[2] this models 1-2 switches and 1-2 km of medium. Serialisation delay (sometimes called transmission delay) and queuing delay are modelled by NS-3 based on the Channel Data Rates. NS-3 does not simulate processing delays.

The simulation duration is 30 seconds. The payload flows start at second 4 and cease at second 24. Between second 8 and 16 a background bulk TCP flow occurs on the 32 Mbit/s uplink. This models a sudden decrease in the path’s capacity to observe how the different scheduling algorithms handle it.

To simulate application traffic we used the NS-3 packet-sink application on \( C0 \rightarrow C2 \) and three bulk send applications on \( S \). This simulates three full speed downloads via TCP.

B. AFMT and Round Robin Implementation

For a first prototype we used TCP as transport protocol for the subtunnels. Since the \( T_{\text{entry}} \) and \( T_{\text{exit}} \) nodes are under the control of the AFMT system we can fully configure the TCP socket to benefit AFMT. The Delayed acknowledgement extension allows TCP to only send an acknowledgement for every second received data segment, or if a timeout occurs, to reduce overhead. NS-3 used a unusual high default of 200ms for the timeout, for accurate tunnel stats we reduced it to the same value the Linux kernel uses: 40ms. TcpNoDelay was enabled to get fast and interactive tunnel behaviour.

When tunnelling datagrams, TCP blurs the packet boundaries, since it’s basically a stream transport protocol[12]. To re-distinguish the payload packets we introduced a small 8 byte header preceding every payload datagram with its size.

For comparison all experiments were also conducted with a round robin MT system in the same network, with the same payload. The round robin (RR) scheduler used UDP for its subtunnels.

C. General Results

The total goodput is shown in table I. All MT systems provide a higher throughput than a single path solution with the fastest uplink. The increase ranges from 21% (three subtunnels RR) to 110% (two subtunnels, AFMT). For three subtunnels AFMT has a 60% higher overall goodput with 105 Mbyte. However with two subtunnels the gap is much smaller with 27%.

This indicates that the dynamic AFMT is better in dealing with diverse paths and path capacity changes. The stable throughput additionally indicates successful flow-aware traffic splitting. Low flow-awareness would have resulted in packet reordering and therefore cwnd reduction and sudden throughput rate drops. But both are considerably reduced compared to RR as described in the following two subsections.

D. Three Subtunnels

For three subtunnels the overall goodput is plotted in Figure 4. AFMT has a consistently higher throughput than RR. It starts at second 4 when the slow start algorithm of the subtunnels opens up the cwnd in the same time the cwnds of the payload flows do. So no initial inertia is visible. After that, until second 8 the goodputs lie around 6.5 MiB/s and 4.2 MiB/s.

At second 8 the gap widens as AFMT goodput drops to about 4 MiB/s and RR to about 1. We assume this is because RR continues to send the same amount of packets over the impaired path, which brings congestion and packet loss. At second 12 AFMT drops down to the same goodput as RR. 1.5 seconds later it recovers back to 4 MiB/s. At second 16 when the background traffic stops, both systems recover. The

| Subtunnels                   | RR | AFMT |
|-----------------------------|----|------|
| Three Subtunnels: 16, 32, 50 Mbit/s | 63.02 | 105.89 |
| Two Subtunnels: 32, 50 Mbit/s    | 87.63 | 111   |
| No Tunnel, Single Path, 50 Mbit/s | 52.7 |

TABLE I

GOODPUT OVER 30 SECONDS IN MiB/BYTES FOR THE DIFFERENT SCHEDULING ALGORITHMS IN DIFFERENT NETWORK TOPOLOGIES
AFMT goodput stays at an average of 5.8 MiB/s, while the RR goodput stays at 4.1.

E. Two Subtunnels

The total goodput over time for both algorithms without the 16 Mbit/s subtunnel is plotted in figure 5. While AFMT opens its cwnds still fast, the difference is smaller. AFMT transports ca. 6.5 MiB/s, RR oscillates around 5.8 MiB/s. At second 8 both throughputs drop and again RR’s throughput drops further to about 2 MiB/s compared to AFMT’s 4 MiB/s. However it is notable that for both systems the throughputs oscillate with larger amplitudes than for three subtunnels. After second 16 both systems recover to their previous throughput rate.

V. RELATED WORK

A. Multipath TCP

A MPTCP scheduler has more options to avoid packet reordering than a MT scheduler. It does not have to consider flowlets and can define new flowlets suitable to avoid packet reordering. For adaptivity, MPTCP trusts the congestion control of its subflows. Every time space in a subflows’ cwnd opens and there is data to send, the scheduler is invoked [9]. LowRTT [10] is a simple scheduler currently used as default in the Linux Kernel. When invoked, it picks the subflow with the lowest available RTT. It reduces head-of-line blocking and delay variation by about 20%.

DPSAF [13] is a sophisticated computation intensive scheduler for vehicular networks. It tries to predict when the packets will arrive and sends them out-of-order, so that they will arrive in order. While DPSAF might be a good solution for vehicular networks with bad connectivity, it is unclear how feasible it is for high speed internet usage.

B. Multipath Tunnelling

[3] proposes a MT system for non-TCP loss-tolerant media traffic and two subtunnel paths with fixed characteristics. A DSL path with high stable bandwidth and a LTE path with low varying bandwidth as overflow vault. It detects packet loss via sequence numbers in a own header and adapts round robin weights accordingly. However, this reimplements existing transport protocol functionality. It is not flow-aware and has to re-order the packets with a reordering buffer.

[5] researches multipath access networking in general. Additionally the author designed a HTTP extension that splits videos in chunks of fixed size and downloads them on separate paths. This needs changes of the client application and only works for a specific case.

VI. CONCLUSIONS AND OUTLOOK

In this paper we proposed AFMT a packet scheduling algorithm for multipath tunnelling that increases throughput and reliability. Several NS-3 simulations including changing path capacities have shown that AFMT effectively deals with diverse and changing network paths.

These results were obtained although the experiments used the suboptimal TCP protocol for the subtunnels. Our future work will evaluate and optimise AFMT characteristics using DCCP with diverse payload traffic.

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