Run, Fatboy, Run:
Applying the Reduction to Uniprocessor Algorithm to Other Wide Resources

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Abstract

The RUN (Reduction to UNiprocessor) [18, 19, 13] algorithm was first described by Regnier, et al. as a novel and elegant solution to real-time multiprocessor scheduling. The first practical implementation of RUN [3] created by Compagnin, et. al., both verified the simulation results and showed that it can be efficiently implemented on top of standard operating system primitives. While RUN is now the proven best solution for scheduling fixed task sets with fixed rate on multiprocessors, further work remains to make it practical for common workloads and on resources other than CPUs.

This technical report briefly describes RUN, then outlines enhancements to enable it to support dynamic task sets, best-effort tasks, and sporadic tasks. It also examines how RUN might be adapted for use in situations involving an array of multiple resources where some form of preemptions and migrations are allowed (although must be minimized). It also describes how buffers can be sanity checked in a system where a RUN-scheduled resource is consuming data from another RUN-scheduled resource.

1 Introduction

The RUN algorithm takes advantage of two features of highly loaded systems. First, a busy system has little idle time, so it makes more sense to solve the dual schedule (i.e. when tasks aren't running). The critical nature of idle time was first noticed by Levin, et al. when they created a theory explaining all previous optimal [1] multiprocessor algorithms [12, 11]. Second, a highly loaded system will generally have many small tasks that can be packed together and treated as one task. Both steps simplify the problem at hand, and when they are combined recursively they produce a reduction tree that partitions the scheduling problem amongst the packings and bounds the interactions between packings.

In a system with N processes and M processors where each process requires a fixed share of a processor, packing shrinks the size of N and taking the dual of the system reduces the size of M whenever $N < 2M$ By alternating packing and dual operations, Regnier, et al. showed that they were able to reduce the difficult multiprocessor problem down to a simple uniprocessor problem. The approach is revolutionary because it is simple and provably more efficient in terms of context switches and migrations than any previous approach (e.g the family of proportionate fairness and deadline partitioning scheduling algorithms).

In the remainder of this technical report, section 2 describes general improvements to RUN that will be necessary for practical deployment. Following that, section 3 describes applications to network hardware queues, queuing disciplines, and route management. Section 4 explores scenarios where RUN might be applicable to storage. Finally, section 5 describes how to semi-automatically debug underflow and oveflow of buffers connecting resources managed by scheduling algorithms like RUN.

2 Refinements

2.1 Best-effort Tasks

RUN was designed to use Earliest Deadline First (EDF) scheduling within packings, but any optimal uniprocessor scheduling algorithm will work. In particular, since RUN already uses knowledge of rates and periods, it would make sense to use the Rate Based Earliest Deadline (RBED) generalization of EDF since it enables integrated scheduling of hard real-time, soft real-time (minimum rate with proportional sharing of slack), and best effort tasks [2].

The theoretical underpinnings of RBED are based

[1] Optimal in the sense that an algorithm will produce a valid schedule for any task set that is feasible.

on the concept of Resource Allocation and Dispatching (RAD) reservations, which are $(rate, period)$ tuples that obsolete priority classes and previously defined rate-limit specifications. Prior non-realtime scheduling methods possess a limited number of relative, coarse-grained classes (priorities), require rates to be strictly satisfisfied for any measured interval (e.g. Token Bucket Filters), have common periods between all tasks, or have a fixed linear mapping between periods to priorities. RAD reservations enable arbitrarily fine-grained Quality of Service (QoS), possess meanings that stay consistent in a dynamic environment, and allow straightforward reasoning about composing end-to-end QoS.

Implementing RUN with EDF is easier than with RBED since EDF only uses the tasks' deadline information. RBED flexibility requires performing an online calculation of a best effort task's rate from the ratio of its individual weight to the total weight of all best effort tasks.

If minimal preemptions with perfect proportional fairness between best-effort tasks is desired, then RUN can accomodate that goal. However, RUN could take advantage of best-effort tasks in a way similar to that of idle slack packing (see section 2.5). A per resource reserve would encourage both schedule partitioning and work conservation. Tasks with guaranteed rates are best-fit packed to the best-effort reserve limit while best-effort tasks are left unassigned. RUN continues with idle slack packing, but when an idle task is executed or a guaranteed task has no work (generating dynamic slack), RBED chooses the next best-effort task that does have work.

Note that the LITMUS-RT implementation of RUN [3] does allow best effort tasks to use the processor when no real-time tasks are scheduled. While this is useful, RUN with RBED would be simpler than a hierarchical scheduler such as that. Also, RBED can support a broad range of quality of service. For instance, some tasks may only need best effort rates, but do require deadlines to be met.

2.2 Dynamic Tasks

The description of RUN, as well as its implementation in simulators and in practice, assumes the entire task set is known a priori and that it doesn't change throughout the life of the system. Certainly this doesn't reflect reality and should be addressed. Furthermore, the work required by the scheduler to adapt to these changes needs to be minimized.

If a task leaves the system, then it can be trivially swapped with an equal idle task without disturbing the schedule (i.e. online slack packing). However, the change in available utilization means that best effort tasks should recalculate their rates and be redistributed in order to maintain perfect proportional sharing. Perhaps it would be best to only do this work for the affected subsystem, even if that results in best effort tasks being treated somewhat unfairly across the entire system.

If a feasible task enters the system and has a rate less than or equal to an idle task, then it can be inserted with little effort. However, if the new task has a rate greater than any one idle task, then RUN must create a new reduction tree. Of course, it would best to maintain the previous reduction tree as much as possible in order to minimize one-time missed deadlines and migration penalties.

In fact, there is an additional constraint in online packing when compared to offline packing: in addition to task utilizations summing to less than or equal to one, the sums of their remaining budget must be less than the time left until the furthest deadline of the packed tasks. This is always a constraint, but one that it is obviously satisfied when the system is offline. Best-effort tasks, like idle tasks, make RUN's job easier for dynamic task sets.

2.3 Sporadic Tasks

Defining all tasks as fixed-rate results in overprovisioning resources for a sporadic task. We refer to this unused utilization as dynamic slack. RUN does not, as of yet, support the sporadic task model, so there is naturally interest in scheduling algorithms that do. It has been an open question whether or not RUN can be directly modified to support sporadic tasks—the original creators of it have, in fact, proposed the Quasi Partitioned Scheduling (QPS) algorithm as an alternative [14].

However, if RUN supports both best effort tasks and dynamic task sets as described above, then it doesn't matter if a sporadic task is defined as a fixed-rate task. The dynamic slack can be used by best effort tasks packed with sporadic tasks.

2.4 Resource Assignment

The creators of RUN were primarily concerned with producing the set of tasks that should run at any given time. Their task-to processor assignment scheme is simple:

1. leave an executing task on its current processor
2. assign idle tasks to their last-used processor
3. assign remaining tasks arbitrarily

For systems expect zero slack or best effort tasks, it might also be worth the effort to keep track of the set of each tasks' m previously used resources. That way, if a task must migrate repeatedly, then it is more likely to migrate within a subset of the resources rather than amongst

all of the resources within its subsystem. In other words, this heuristic should help on NUMA systems where the cost of migration becomes much larger between NUMA nodes.

2.5 Offline Bin Packing

The effectiveness of the pack step in RUN's offline reduction phase determines the performance of the algorithm in terms of the number of preemptions caused per job. The authors prove that each release event in a p-level reduction tree causes at most $\lceil (p+1)/2 \rceil$ preemptions, and so RUN suffers an average of no more than $\lceil (3p+1)/2 \rceil$ preemptions per job. Therefore, we are interested in packing heuristics that minimize both the number of reduction levels and the number of release events.

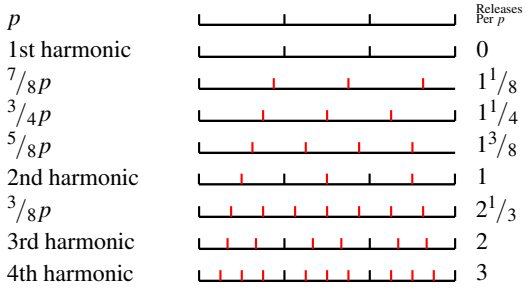
The authors found that most packing heuristics achieved the same number of reduction levels as long as the task rates were sorted in descending order. Best Fit Descending achieves fewer preemptions and migrations than the others due to its packing of high rate tasks together first. Worst Fit Descending performs worse in this regard because it spreads out high rate tasks among bins, increasing the likelihood that one of those tasks must be preempted more often.

High rate tasks are at greater risk of suffering preemption than low rate tasks because they utilize a greater percentage of their period. If high rate tasks are packed together first, as in Best Fit Descending, then short period tasks are limited in the number of tasks they can preempt. Likewise, a long period task can only be preempted by a limited number of tasks. This vulnerability of high rate tasks also helps explain the humps in preemptions and migrations in Levin's figure 3.10 [13]. With a number of tasks, t, and resources m, the tasks are particularly vulnerable when $m < t < 2m$ on a fully utilized system.

Intuitively, one would expect tasks with similar periods (e.g. harmonic) to decrease the number of release events, and Levin did report testing that hypothesis with a Least Common Multiple (LCM) Fit heuristic in his thesis. While LCM-fit sometimes results in trees with more reduction levels, it still achieves 4-5% fewer premptions and migrations. Unfortunately, it comes at the cost of signficantly greater algorithmic complexity.

By analyzing the number of additional events when a long period task is packed with successively shorter period tasks in figure 1, we can see how LCM-fit fails to minimize some events. When periods shorten, as in tasks 8 and 9, the least common multiple remains small with task 1, but the number of release events continues to increase. If several tasks with the same periods are encountered, then the packing benefits from overlapping events. However, it would be better to pack a few tasks that were within half a period length of a long task rather than a few beyond the 2nd harmonic.

Figure 1: The Effect Of Period Length On Events



In addition to measuring the preemptions caused per job, it would be illuminating to compare preemptions per time unit. Since small rate jobs are less likely to be preempted, the number of preemptions per job could look low even if the per time unit count is high.

There are considerations other than the number of preemptions that might make a heuristic attractive. Below are brief descriptions of some different packing heuristics and when they might be most useful.

Slack Packing As described in the original paper, Slack Packing increases the number of independent partions (decreasing migrations) when the system utilization is less than 100%. By adding idle tasks at the end of the first packing (regardless of primary packing heuristic).

Worst Fit Decreasing Rates Optimizes spreading large tasks amongst resources, making it suitable for less highly loaded situations or when it is more important to use each resource rather than using fewer resources. For instance, this would benefit parallel applications.

Best Fit Decreasing Rates Minimizes the number of packings and reduction levels (minimizes preemptions and migrations), so it would be suitable for highly loaded situations or when it is more important to use fewer resources than using all resources.

These heuristics have already been evaluated in terms of performance (i.e. preemptions and migrations) by the original authors. Further work would be necessary to determine which would be appropriate for a power saving policy. It might be that it would be necessary to switch between Worst and Best Fit, as the former might allow all processors to finish more quickly where the latter could keep some cores off entirely.

Certainly other heuristics exist, but among these Slack Packing with Best Fit Decreasing Rates is both simple to implement and one of the best performing heuristics.

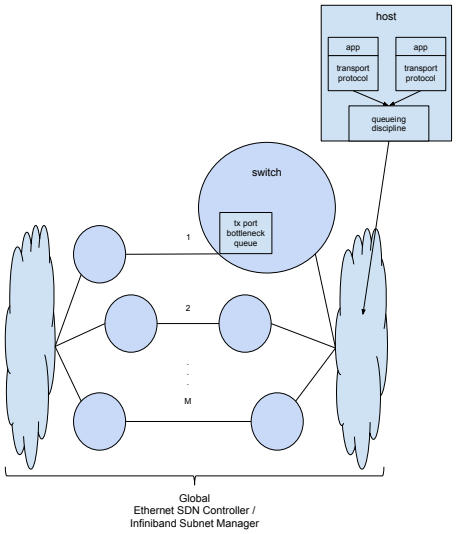
2.6 Affinity

Some work needs to be done to make RUN support resource affinity. This is common in the case of processes in a NUMA system that want to be as close to an attached device (e.g. network card or GPU) as possible. Affinity can be thought of as a partial pre-specification of the packings and placements. Pinning a task to a single resource should be easy to take into account, and regular recurring sets (i.e. a NUMA nodes) should also be straightforward to support. However, arbitrary affinity sets may be unworkable since they might over-constrain the packing problem. At any rate, affinity support in RUN requires further investigation.

3 Networking

Providing QoS on networks is complex because several independent resources must be managed in concert: transmission and reception queues on the communicating hosts and the transmission queues on the switches. As figure 2 shows, flow is affected by the route it takes, the bottlenecks on that route, and the manner in which a host sends its data.

Figure 2: Network QoS Layers



Traditional traffic shaping, even combined with a global routing algorithm ensuring that routes aren't overloaded, could still allow a bottleneck queue to build up and drop packets. The bottleneck would have to be able to handle the worst case simultaneous burst from every flow on that route [10]. Furthermore, even lossless networks such as Infiniband suffer from congestion in the form of congestion trees and the Parking Lot Problem [4, 5, 21]. In practice, Infiniband's congestion control isn't enabled because it must be tuned to the specific traffic patterns of the system. If the traffic changes, then overall throughput can be badly hampered.

Therefore, in traditional networks, the transport protocol still needs to adapt to congestion in order to minimize bottleneck queue usage. Alternatively, if switches implemented real-time scheduling algorithms such as RUN, congestion wouldn't exist. Alizadeh, et al. showed how EDF might be implemented efficiently in pFabric [1]. It will be interesting to explore whether RUN with RBED might also be implemented efficiently for packet switching.

3.1 Host Hardware Queues and Qdiscs

Modern network interface hardware often possesses multiple queues, and Linux has supported them since the 2.6.27 kernel. That support currently allows an administrator several options, including pinning hardware queues to cores or NUMA nodes. While that minimizes context switches and maximizes cache use, it suffers from head-of-line blocking. Alternatively, a round-robin scheduler can be used. While being fair and avoiding head-of-line blocking, round-robin necessarily hurts efficiency. This presents another opportunity for the RUN algorithm. It has provably low numbers of migrations, and can prevent head-of-line blocking while enforcing QoS.

In addition to the multiqueue support already mentioned, a network classifier control group can tag packets to be handled by specific software queueing disciplines (qdiscs). Some of the existing qdiscs are Token Bucket Filters, Stochastic Fair Queueing, Fair Queuing Controlled Delay (FQ_codel), Random Early Detection, and Proportional Integral controller Enhanced. Each of these is an attempt to mitigate congestion or reduce buffer bloat in the network. Most of them concentrate on providing fairness, some provide coarse-grained QoS with priority classes.

Only one qdisc, the Hierarchical Fair Service Curve, claims to support real-time traffic. Configuring a hierarchy of qdiscs to classify and shape traffic is not trivial, and in general must be fine tuned to the network. Even FQ_codel, a "knobless" qdisc still requires tuning and some sort of rate-limiting qdisc working in conjunction with it. Furthermore, it is not intended for datacenter networks.

Since RUN can schedule flows according to QoS constraints across multiple hardware queues, it should be much simpler to configure. It would need to at least be able to distinguish packets according to flow, if not subflows multiplexed over a single connection. In that case, RUN would need to work in concert with a control group designed to tag packets with $(rate, period)$ information,

in addition to the existing network priority control group.

By creating a RUN qdisc, not only will packets transmitted by Linux hosts be scheduled according to modern real-time theory, but it could lead to a RUN-based network fabric. The Open Virtual Switch (OVS) module in the Linux kernel is intended to be used for both virtual machine networks as well as the operating system on hardware switches, and OVS uses the existing Linux qdiscs to enforce its QoS. Other Linux-based switches also exist. The efficacy of RUN can first be tested using Mininet [9], and then on real hardware.

3.2 Routes

In general, it is unlikely that RUN can be directly applied to global load balancing of routes. However, if the switches themselves use RUN as just described, then they should be able to provide valuable information to a global load balancing algorithm: the amount of unreserved rate (i.e. static slack), dynamic slack, number of best-effort flows, which flows are underflowing or overflowing and whether they blame upstream or downstream. This information, while simple, should be much more useful to a global scheduler than basic rate and drop information. The rest of this section discusses why it would be nice to use RUN for route management and why it is difficult to apply it.

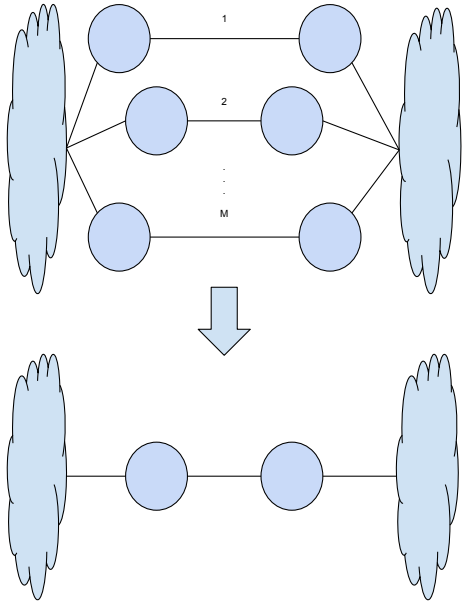
The edges of networks present an interesting opportunity for RUN. Whether it is a global WAN gateway where bandwidth is extremely limited and precious or the high performance interconnect between a supercomputer and a parallel filesystem, flows should maximize the utilization of the available routes while preventing congestion and data loss. And in cases where there are multiple links or paths that immediately reconverge on the other side, as in figure 3, RUN can be applied.

As opposed to traditional distributed multipath routing approaches described by Hopps [6], RUN would be used by a SDN (Software Defined Network) Controller or a Subnet Manager (in the case of Infiniband) to assign routes to flows after they have passed the standard RAD admission control test: Would the new flow's rate cause the total flow rate to exceed capacity?

To be clear, RUN would not be discovering the topology of the network. It is scheduling the routes given to it to manage. Also, it would take further work to make RUN take considerations other than a path's cost (e.g. security) into account.

Can RUN be used in the case where the multiple routes aren't immediately recombined as Jain, et al. addressed with B4 [7]? Perhaps, but there are two big concerns. First, how would one partition the graph so that at least the left hand side of the routes looks identical from RUN's perspective? In other words, if the graph is

Figure 3: Reduce to Unipath



simply bisected, then RUN assumes that any route will work and could overload the left side of the graph. It appears RUN would have to execute recursively on the graph from the edges inward.

That brings up the second concern: when RUN schedules a task it may migrate between several of the resources. At that point, the single fixed-rate task becomes a sporadic task on each of those resources. Treating them each as fixed-rate will quickly exhaust the resources even though best effort flows could suck up the dynamic slack. So, even a hard real-time flow would be forced to become several best-effort flows, and thus comprise the original guarantee. An additional concern arises from the best effort tasks. Just because they can use up the dynamic slack at one hop doesn't mean the next hop can handle the burst.

4 Storage

This section is more brief than section 3 because it is not the current focus of the authors' research. However, we share our thoughts concerning RUN as applied to storage below. In general, RUN isn't a clear win for scheduling arrays of storage devices since content is not replicated everywhere. However, RUN could be useful in some scenarios, but would have to fold in lessons learned from Fahrrad and other real-time storage work done at UC Santa Cruz [16, 17, 8].

4.1 Multiqueue

Linux is in the process of gaining multiqueue support for storage, just as it did for networking. The block layer gained support first, and it is being followed by the SCSI and Device Manager subsystems. At this point, hardware drivers like NVMe are just beginning to exploit the block device support. From discussions on the mailing list, it appears that the I/O scheduler may be last to gain multiqueue support, and it might be an entirely new "deadline-ish" scheduler rather than a modification to the standard CFQ scheduler.

4.2 Reading or Modifying Existing Non-replicated Data

If data isn't replicated across all devices, RUN can incorporate reads or modifications to a file or object into its schedule if the task specification (i.e. RAD reservation) includes affinity information.

4.3 Writing New Data

On a distributed system, when the question arises where to store new data, RUN would not be constrained by task affinities and be able to freely manage performance after other considerations, such as available space are answered.

4.4 Reading from Replicas

Parallel file systems often replicate data between multiple servers. Usually one server is considered the primary, but it can become overloaded and want to balance its client load with its replicas. As long as consistency among replicas is maintained (trivially true for read-only access), then RUN might be used to schedule use of the replicas. If the distributed storage system uses per server replicas, RUN should work well.

Unfortunately, with regard to Ceph's per-object replicas [20], RUN may not be a good fit. The problem is that different objects won't necessarily share the same set of storage backends. Instead of having many independent RUN schedulers in control of distinct subsets of resources, you would need one instance of RUN scheduling all resources and complicated affinity sets. So RUN might work in this case, but it wouldn't be as parallelized and the affinity of disjoint sets makes the packing problem much harder. It may even constrain the bin packing problem enough that a good packing cannot be found. This problem deserves further thought.

5 Buffer Analysis

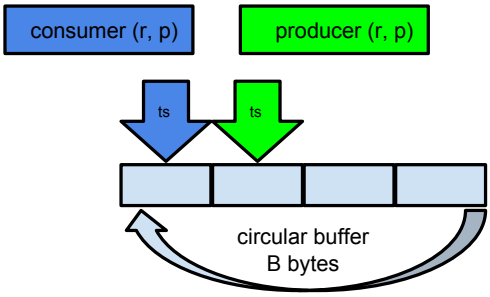
If RAD schedulers are operating according to their design, then performance is guaranteed. But the RAD model also enables sanity checking on the buffers between schedulers. A producer-consumer model, RAD-Flows [15], derives equations 1 and 2 describing the amount of buffer space B_{max} and time T_{max} is the amount of time it should take for the entire buffer to be rewritten for a well behaved producer/consumer pair of two interacting RAD $(rate, period)$ reservations (r_p, p_p) and (r_c, p_c).

$$T_{max} = \begin{cases} 2p_c & \text{if } p_p \leq p_c \\ 3p_p & \text{if } p_p > p_c \end{cases} \quad (2)$$

Given this knowledge, If an application suffers from overflow or underflow, RAD-Flow buffers can always point you toward the problem. You can also guard against the unlikely situation where all RAD schedulers in a chain are misbehaving by producing and consuming too quickly.

The following examples assume that a single circular buffer, as shown in figure 4 can be efficiently accessed simultaneously by the producer and consumer, and a timestamp is recorded whenever there is an attempt to move a pointer. Since we know the amount of time it takes to rewrite a RAD-Flow buffer, the simple circular buffer is sufficient to illustrate the general approach for other buffer data structures.

Figure 4: Circular RAD Buffer



The examples apply to both blocking and non-blocking producers. In the blocking case, overflow doesn't result in lost data and RAD allows us to determine whether the producer is blocking because it is attempting to write too quickly or whether the consumer caused the block by reading too slowly. Non-blocking producers will lose overflowing data and the same tests identify whether the producer or consumer bears responsibility.

If the producer pointer circles around to the consumer

$$B_{max} = \begin{cases} 2\left(\left\lceil \frac{p_c}{p_p} \right\rceil + 1\right) r_p p_p - r_p p_p & \text{if } p_p \leq p_c \\ 2 r_p p_p + \max\left(0, r_p p_p - \left(\left\lfloor \frac{p_p}{p_c} \right\rfloor - 1\right) r_c p_c\right) & \text{if } p_p > p_c \end{cases} \quad (1)$$

pointer (buffer overflow), then there are three possibilities:

1. the producer is sending faster than its reservation
2. the consumer is too slow
3. both 1 and 2

Since the producer has overtaken the consumer, we know that it has rewritten the entire buffer from the consumer pointer on. It must have written to the consumer's location before the current value of the consumer timestamp. Because the buffer was sized according to the RAD reservations, we know the producer's pointer should not arrive at the consumer pointer's location before $ts_c + T_{max}$. Equation 3 uses that information to determine which party is to blame for overflow, and figures 5 and 6 give examples of both cases.

$$\text{producer} = \begin{cases} \text{fast} & \text{if } ts_p - ts_c < T_{max} \\ \text{slow} & \text{if } ts_c - ts_p \geq T_{max} \end{cases} \quad (3)$$

Figure 5: Overflowing RAD Buffer

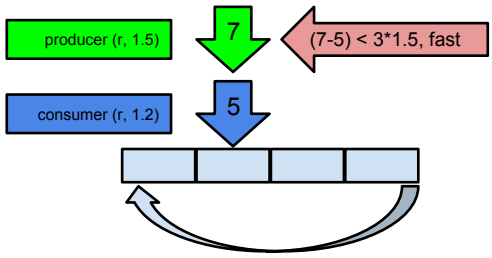
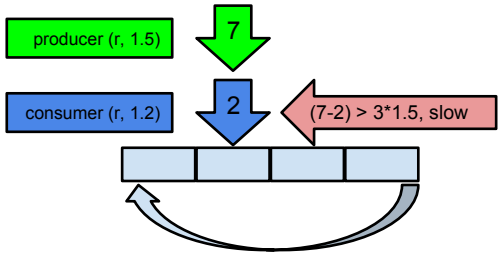


Figure 6: Underflowing RAD Buffer



Similarly, a buffer is underflowing when the consumer pointer circles to the producer pointer. Equation 4 is a mirror to equation 3.

$$\text{consumer} = \begin{cases} \text{fast} & \text{if } ts_c - ts_p < T_{max} \\ \text{slow} & \text{if } ts_p - ts_c \geq T_{max} \end{cases} \quad (4)$$

If both the producer and consumer are misbehaving, then overflow will be blamed on the producer and underflow will be blamed on the consumer. Once their issues are fixed, the buffer will continue to overflow or underflow, but the remaining bad actor will be blamed.

With a chain of reservations, an overflowing upstream consumer might be the victim of a slow downstream consumer. So, if there are several overflowing buffers in a row connecting a chain of RAD reservations, then the blame falls on the furthest downstream consumer. Similarly, the blame for a chain of underflowing buffers percolates up to the furthest upstream producer.

There is another mode of misbehavior that is more difficult to detect. If the producer and consumer are speed-matched but operating too fast or too slowly, then they won't overflow or underflow. However, as long as one part of a chain is behaving correctly, it will point in the direction of bad behavior. The only behavior dangerous to the system as a whole is when all producers and consumers in a chain are too fast. This can be guarded against with a pair of timestamps associated with the beginning of the buffer to track the last time it was produced or consumed (pick one). Whenever the beginning is accessed, the current time is compared to the last time and T_{max}, see equation 5.

$$\text{both fast} \quad \text{if } ts_{now} - ts_{head} < T_{max} \quad (5)$$

In practice, comparisons will need to tolerate some small room for error to account for scheduling quanta and small indeterminate overheads in timekeeping, etc.

The final case of misbehavior is when every producer and consumer in the chain are too slow, but that would only happen when the ultimate producer is slow. In other words, it will only happen when an application is using a fraction of its reservation. This is not a danger to the system and best-effort applications can benefit from the dynamic slack. References

Conclusion

RUN is an elegant algorithm with immense power, and it should enable comprehensive QoS across many layers

and types of resources. Since RUN schedules are valid regardless of task-to-resource assignment strategy, packing scheme (e.g. Worst Fit, Best Fit, Harmonic Period), or which optimal single resource scheduling algorithm is used. This means that RUN has the flexibility to support a policy best suited for the purpose at hand: power efficiency, performance, simplicity, NUMA support, etc.

This tech report only briefly explores how the Reduction to Uniprocessor algorithm can be applied to other resources. In particular, the Radon Network QoS project will be implementing and evaluating RUN combined with RBED in the near future. In addition, RAD buffer theory provides the ability to automatically debug misbehavior.

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