Presentation Slides

Chapter 12

Ring Behavior
(Supplemental Simulations)

Logically Determined Design:
Clockless System Design With NULL Convention Logic

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John Wiley & Sons, Inc.

Ring Simulations

Rings with equal delay stages

The first study holds the number of pipeline stages constant at 24 and varies the number of data wavefronts in the ring moving from wavefront limited behavior to bubble limited behavior.

The second study holds the number of data wavefronts constant at 4 and varies the number of pipeline stages in the ring moving from wavefront limited behavior to bubble limited behavior.

Rings with one slow stage

The third study holds the number of pipeline stages constant at 24 and varies the number of data wavefronts in the ring moving from wavefront limited behavior to bubble limited behavior.

The fourth study holds the number of data wavefronts constant at 4 and varies the number of pipeline stages in the ring moving from wavefront limited behavior to bubble limited behavior.

24 Pipeline Stages With Varying DATA Waves
Equal Delay Stages

24 stages (**P** = 24) with equal stage delays for both DATA and NULL
and a data wavefront population varying from **D** = 0 to 12.

Stage Forward latency = 3 tics
Stage Reverse latency = 4 tics
Slowest cycle time =7 tics

Wavefront rejoin period for ring = 23*3 = 72tics
Bubble rejoin period for ring = 24*4 = 96 tics

Simulation Movies

ring 24 bal movie

1 DATA wavefront Introduction to movies

2 DATA wavefronts

3 DATA wavefronts

4 DATA wavefronts

5 DATA wavefronts

6 DATA wavefronts

7 DATA wavefronts

8 DATA wavefronts

9 DATA wavefronts

10 DATA wavefronts

11 DATA wavefronts

12 DATA wavefronts

24 Pipeline Stages With Varying DATA Waves
Equal Delay Stages, Summary

We begin with 1 data wavefront. Well within the wavefront limited domain. As we increase the wavefronts to 5 we find that the wavefront population period is 70. Just 2 short of the forward latency. The bubble population period is 98. Just 2 beyond the reverse latency of 96. All of this means that the tail wavefront is just 2 tics ahead of the head wavefront. The bubble generated by the tail always waits 2 tics for the head wavefront to arrive. The bubbles encompass the ring and wavefronts flow freely.

With 6 data wavefronts, the wavefront population period becomes 84. Well beyond the forward latency of 72 and the ring transitions to bubble limited behavior. The bubble population period becomes 84. Well short of the reverse latency of 96. The bubbles do not encompass the ring and wavefronts bump into each other and have to wait on bubbles to get around the ring.

24 Pipeline Stages With Varying DATA Waves
Equal Delay Stages, Simulation Data

Pipeline stages	wave fronts	bubbles	slowest cycle	wavefront population period	wavefront rejoin period	bubble population period	bubble rejoin period	Limit period	Through put /period	Through put /50 tics	
24	0	24	7	0	72	168	96	0	0	0	
24	2	22	7	14	72	154	96	72	2	1.39	wavefront limited
24	4	20	7	28	72	140	96	72	4	2.78	
24	6	18	7	42	72	126	96	72	6	4.17	
24	8	16	7	56	72	112	96	72	8	5.56	
24	10	14	7	70	72	98	96	72	10	6.94	
24	12	12	7	84	72	84	96	96	12	6.25	bubble limited
24	14	10	7	98	72	70	96	96	10	5.21	
24	16	8	7	112	72	56	96	96	8	4.17	
24	18	6	7	126	72	42	96	96	6	3.13	
24	20	4	7	140	72	28	96	96	4	2.08	
24	22	2	7	154	72	14	96	96	2	1.04	
24	24	0	7	168	72	0	96	0	0	0	

8 Wavefronts With Varying Pipeline Stages
Equal Delay Stages

Number of wavefronts is constant 8
delay of all stages is equal for both DATA and NULL
The number of pipeline stages varies from 8 to 24.

Stage Forward latency **FL** = 3 tics
Stage Reverse latency **RL** = 4 tics
Slowest cycle time = 7 tics

Wavefront rejoin period for ring = stages*3 tics
Bubble rejoin period for ring = stages*4 tics

Simulation Movies

ring N bal movie

8 pipeline stages
9 pipeline stages
10 pipeline stages
11 pipeline stages
12 pipeline stages
13 pipeline stages

14 pipeline stages
15 pipeline stages
16 pipeline stages
17 pipeline stages
18 pipeline stages
19 pipeline stages

20 pipeline stages
21 pipeline stages
22 pipeline stages
23 pipeline stages
24 pipeline stages

4 DATA Waves With Varying Pipeline Stages
Equal Delay Stages
Summary

We begin with 24 stages. Well within the wavefront limited domain. As we decrease the stages to 19 we find that the wavefront population period 56 is Just 1 short of the 19 stage wavefront rejoin period. The bubble population period is 77, Just 2 beyond the 19 stage bubble rejoin period of 76. All of this means that the end wavefront is just 1 tic ahead of the lead wavefront. The bubble generated by the end always waits 1 tic for the lead wavefront to arrive. The bubbles encompass the ring and wavefronts flow freely.

With 18 pipeline stages, the wavefront rejoin period becomes 54. Short of the wavefront population period of 56 and the ring transitions to bubble limited behavior. The bubble population period becomes 70. Short of the 18 stage bubble rejoin period of 72. The bubbles do not encompass the ring and wavefronts bump into each other and have to wait on bubbles to get around the ring.

8 Wavefronts With Varying Pipeline Stages
Equal Delay Stages
Simulation Data

Pipeline stages	wave fronts	bubbles	slowest cycle	wavefront population period	wavefront rejoin period	bubble population period	bubble rejoin period	Limit period	Through put /period	Throughput /50 tics	
24	8	16	7	56	72	112	96	72	8	5.56	wavefront limited
23	8	15	7	56	69	105	92	69	8	5.80	
22	8	14	7	56	66	98	88	66	8	6.06	
21	8	13	7	56	63	91	84	63	8	6.35	
20	8	12	7	56	60	84	80	60	8	6.67	
19	8	11	7	56	57	77	76	57	8	7.02	
18	8	10	7	56	54	70	72	72	10	6.94	bubble limited
17	8	9	7	56	51	63	68	68	9	6.62	
16	8	8	7	56	48	56	64	64	8	6.25	
15	8	7	7	56	45	49	60	60	7	5.83	
14	8	6	7	56	42	42	56	56	6	5.36	
13	8	5	7	56	39	35	52	52	5	4.81	
12	8	4	7	56	36	28	48	48	4	4.17	
11	8	3	7	56	33	21	44	44	3	3.41	
10	8	2	7	56	30	14	40	40	2	2.50	
9	8	1	7	56	27	7	36	36	1	1.39	
8	8	0	7	56	24	0	32	0	0	0	

Pipeline Ring Performance
Equal Delay Stages

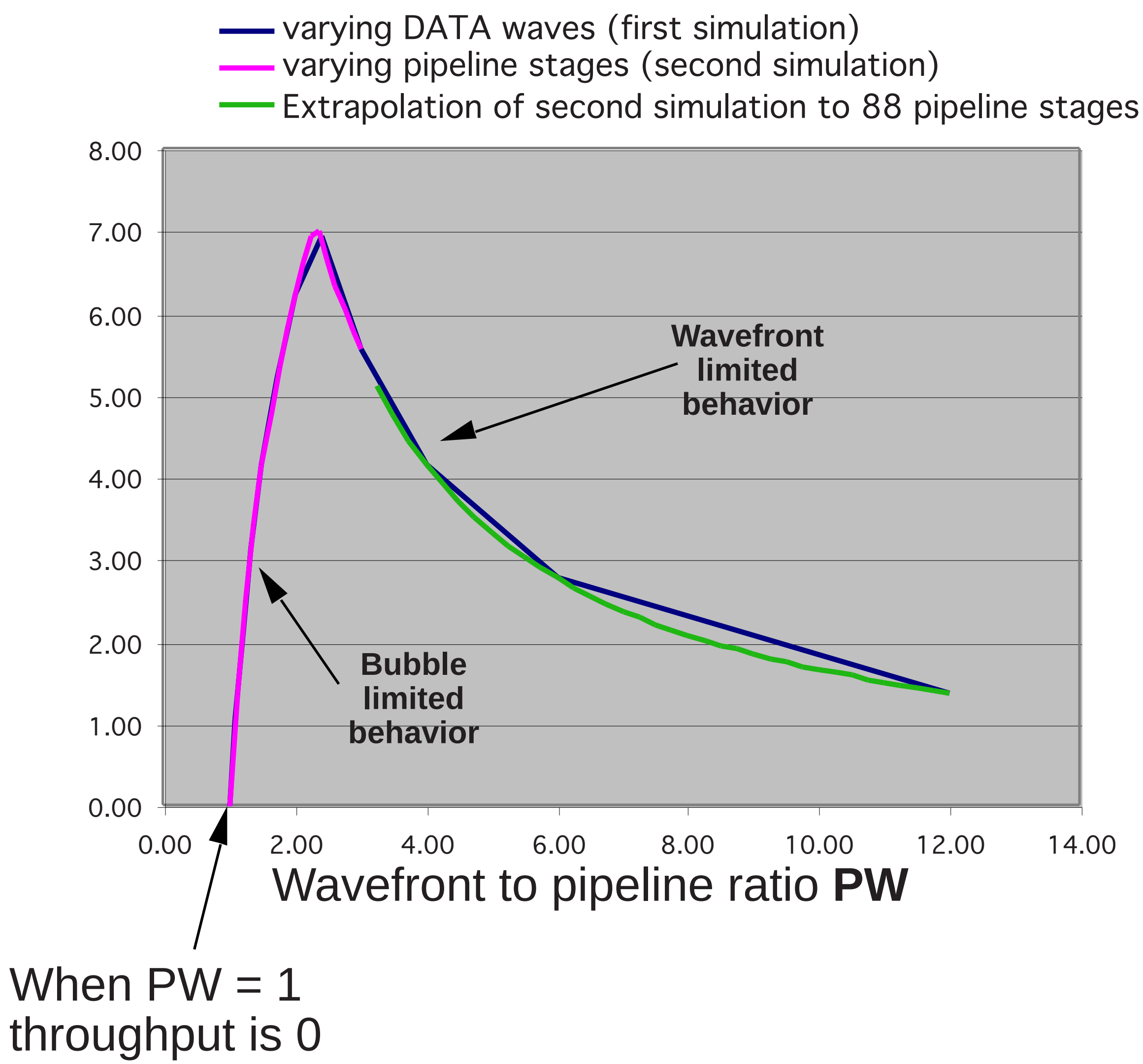
The examples so far have shown a ring with all stages having equal delay. This is the simplest form of pipeline ring. The throughput depends on the timing characteristics of each stage and on the ratio of pipeline stages to data wavefronts in the ring (PW). Peak throughput was observed with PW ≈ 2.4 pipeline stages per data wavefront.

This is for a ring with no propagation delay in the data path between registers. The delays are solely register and completion logic delays. With larger delays in the data path, peak performance approaches PW = 1.0.

PW > 2.4 The ring is wavefront limited. There is always sufficient bubble for the wavefronts to flow through so the wavefronts will flow at full rate and will never be blocked. Bubbles wait on wavefronts.
1.0 < PW < 2.4 The ring is bubble limited. There are always sufficient wavefronts to flow through a bubble so the bubble travels at full rate around the ring backwards. Wavefronts wait on bubbles.
PW = 1.0 There are no bubbles for wavefronts to flow through and the ring is deadlocked.

Pipeline Ring Performance

For ring with identical delays for all stages and for DATA and NULL



Ring With a Single Slow Delay Stage

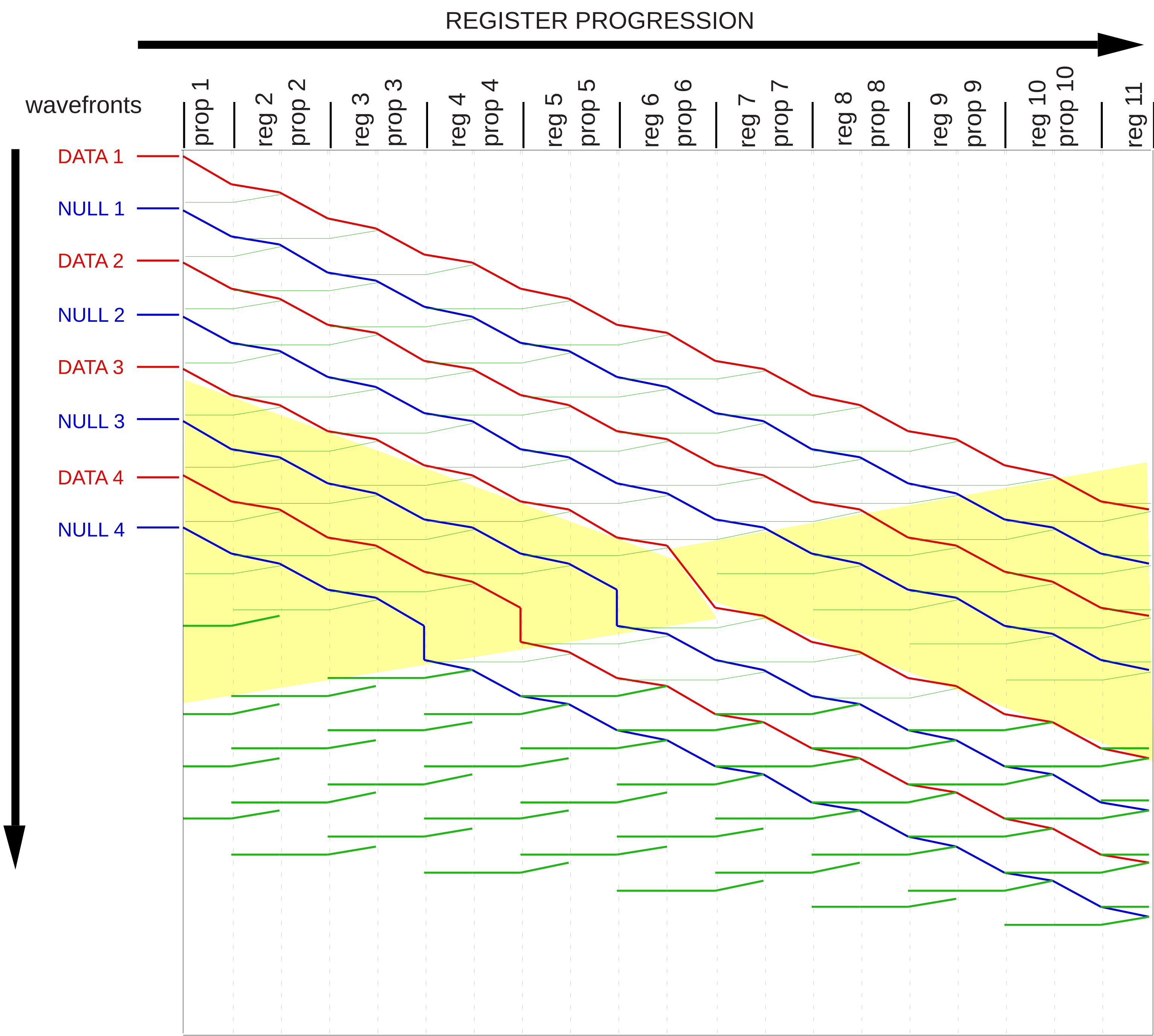
A persistently slow stage will continually shadow all the other stages in the ring and all the other stages will have to wait on the slow stage. The slow stage will dominate and limit the throughput of a ring just like a slow stage dominates and limits the throughput of an open pipeline.

This slow stage can be due to an delay in a stage or a wait caused by an interaction with external pipeline structures.

While the faster stages will have to wait on the slow stage they still provide fast rejoin periods around the ring and this makes for the very surprising phenomena of delay limited ring behavior.

We present two simulations of rings with one delay of 4 tics in the data path of one stage of the ring.

A Single Long Delay Shadow in a Ring



Imagine the right edge connected to the left edge (reg 11 feeds into prop 1). The delay sends a bubble delay backwards and an equal wavefront delay forward. On the opposite side of the ring these two shadow delays will meet and exactly cancel.

A persistently slow stage will continually generate shadows and will dominate the performance of the pipeline.

24 Pipeline Stages With Varying DATA Waves
4 Tic Delay in One Stage

Number of stages is constant = 24
One stage has a delay of 4 tics in its data path. all other stages are equal delay
The wavefront population varies from 0 to 24.

Stage Forward latency = 3 tics
Stage Reverse latency = 4 tics
Slowest cycle time =11 tics

Wavefront rejoin period for ring = 24*3+4 = 76 tics
Bubble rejoin period for ring = 24*4 = 96 tics

Simulation Movies

ring 24 bal del movie

1 DATA wavefront
2 DATA wavefronts
3 DATA wavefronts
4 DATA wavefronts
5 DATA wavefronts
6 DATA wavefronts
7 DATA wavefronts
8 DATA wavefronts
9 DATA wavefronts
10 DATA wavefronts
11 DATA wavefronts
12 DATA wavefronts

24 Pipeline Stages With Varying DATA Waves
4 Tic Delay in One Stage

We begin with 1 data wavefront. Within the wavefront limited behavior domain. As we increase the data wavefronts to 2 and 3 we find that the wavefront population period increases to 44 and 66. Just 10 short of the wavefront rejoin period of 76. When a wavefront traverses the delay stage the stage has to wait for the next wavefront. The bubble population period is 198, well above the bubble rejoin period of 96. The delay stage does not have to wait for bubbles.

With 4 data wavefronts, the wavefront population period becomes 88, beyond the wavefront rejoin period of 76. The wavefronts have wrapped around the ring but instead of bumping into each other and waiting on bubbles they are waiting on the delay stage and the ring transitions to delay limited behavior. The bubble population period becomes 176, still beyond the bubble rejoin period of 96.

There is always a wavefront waiting to enter the delay and a bubble waiting to receive a wavefront from the delay. The delay stage does not have to wait on either wavefronts or bubbles and free flows at its full rate. In this domain the ring will operate at the throughput of the delay stage. The appearance in the signal waveforms is that wavefronts are free flowing with no waiting at all. This identical behavior, remarkably, will continue through 5, 6 and 7 data wavefronts. This is a somewhat surprising behavior. One keeps adding wavefronts to the ring without affecting the throughput performance of the ring.

With 8 data wavefronts the bubble population period becomes 88 and falls below the bubble rejoin period of the ring and the ring transitions to bubble limited behavior. Wavefronts emerging from the delay stage now have to wait on a bubble.

24 Pipeline Stages With Varying DATA Waves
4 Tic Delay in One Stage
Simulation Data

Pipeline stages	wave fronts	bubbles	slowest cycle	wavefront population period	wavefront rejoin period	bubble population period	bubble rejoin period	Limit period	Through put /period	Throughput /50 tics	
24	0	24	11	0	76	264	96	0	0	0	
24	2	22	11	22	76	242	96	76	2	1.32	wavefront limited
24	4	20	11	44	76	220	96	76	4	2.63	wavefront limited
24	6	18	11	66	76	198	96	76	6	3.95	wavefront limited
24	8	16	11	88	76	176	96	11	1	4.55	delay limited
24	10	14	11	110	76	154	96	11	1	4.55	delay limited
24	12	12	11	132	76	132	96	11	1	4.55	delay limited
24	14	10	11	154	76	110	96	11	1	4.55	delay limited
24	16	8	11	176	76	88	96	96	8	4.17	bubble limited
24	18	6	11	198	76	66	96	96	6	3.13	bubble limited
24	20	4	11	220	76	44	96	96	4	2.08	bubble limited
24	22	2	11	242	76	22	96	96	2	1.04	bubble limited
24	24	0	11	264	76	0	96	0	0	0	

4 DATA Waves With Varying Pipeline Stages
4 Tic Delay in One Stage

Number of wavefronts is constant = 8
One stage has a delay of 4 tics in its data path. all other stages are equal delay
The number of pipeline stages varies from = 0 to 24.

Stage Forward latency = 3
Stage Reverse latency = 4 tics
Slowest cycle time =11

Wavefront rejoin period for ring = stages*3+4 tics
Bubble rejoin period for ring = stages*4 tics

Simulation Movies

ring N bal del movie

8 pipeline stages
9 pipeline stages
10 pipeline stages
11 pipeline stages
12 pipeline stages
13 pipeline stages

14 pipeline stages
15 pipeline stages
16 pipeline stages
17 pipeline stages
18 pipeline stages
19 pipeline stages

20 pipeline stages
21 pipeline stages
22 pipeline stages
23 pipeline stages
24 pipeline stages

4 DATA Waves With Varying Pipeline Stages
4 Tic Delay in One Stage

We begin with 24 stages. As it turns out this is already in the delay limited domain. The wavefront population period is 88, well beyond the wavefront rejoin period of 76 for 24 stages. The bubble population period is 176, well beyond the bubble rejoin period of 96 for 24 stages. Both wavefronts and bubbles should be waiting and they are. They are waiting on the delay stage and the ring is in delay limited mode.

The ring continues in delay limited behavior as we reduce the stages to 13. The throughput of the ring is identical for all these configurations.

With 12 stages the bubble population period falls below the bubble rejoin period and the ring transitions to bubble limited behavior. The bubbles no longer span the ring and when a wavefront traverses the delay stage it has to wait for a bubble to show up to proceed.

At 30 stages the wavefront population period falls below the wavefront rejoin period which becomes 94 and the ring enters wavefront limited behavior. The rings no longer span the ring and when a wavefront has traversed the delay stage the stage must wait for the next wavefront to arrive.

8 Wavefronts With Varying Pipeline Stages
4 Tic Delay in One Stage
Simulation Data

wavefront limited

Pipeline stages	wave fronts	bubbles	slowest cycle	wavefront population period	wavefront rejoin period	bubble population period	bubble rejoin period	Limit period	Through put /period	Throughput /50 tics
24	8	16	11	88	76	176	96	11	1	4.55
23	8	15	11	88	73	165	92	11	1	4.55
22	8	14	11	88	70	154	88	11	1	4.55
21	8	13	11	88	67	143	84	11	1	4.55
20	8	12	11	88	64	132	80	11	1	4.55
19	8	11	11	88	61	121	76	11	1	4.55
18	8	10	11	88	58	110	72	11	1	4.55
17	8	9	11	88	55	99	68	11	1	4.55
16	8	8	11	88	52	88	64	11	1	4.55
15	8	7	11	88	49	77	60	11	1	4.55
14	8	6	11	88	46	66	56	11	1	4.55
13	8	5	11	88	43	55	52	11	1	4.55
12	8	4	11	88	40	44	48	48	4	4.17
11	8	3	11	88	37	33	44	44	3	3.41
10	8	2	11	88	34	22	40	40	2	2.50
9	8	1	11	88	31	11	36	36	1	1.39
8	8	0	11	88	28	0	32	0	0	0

delay limited

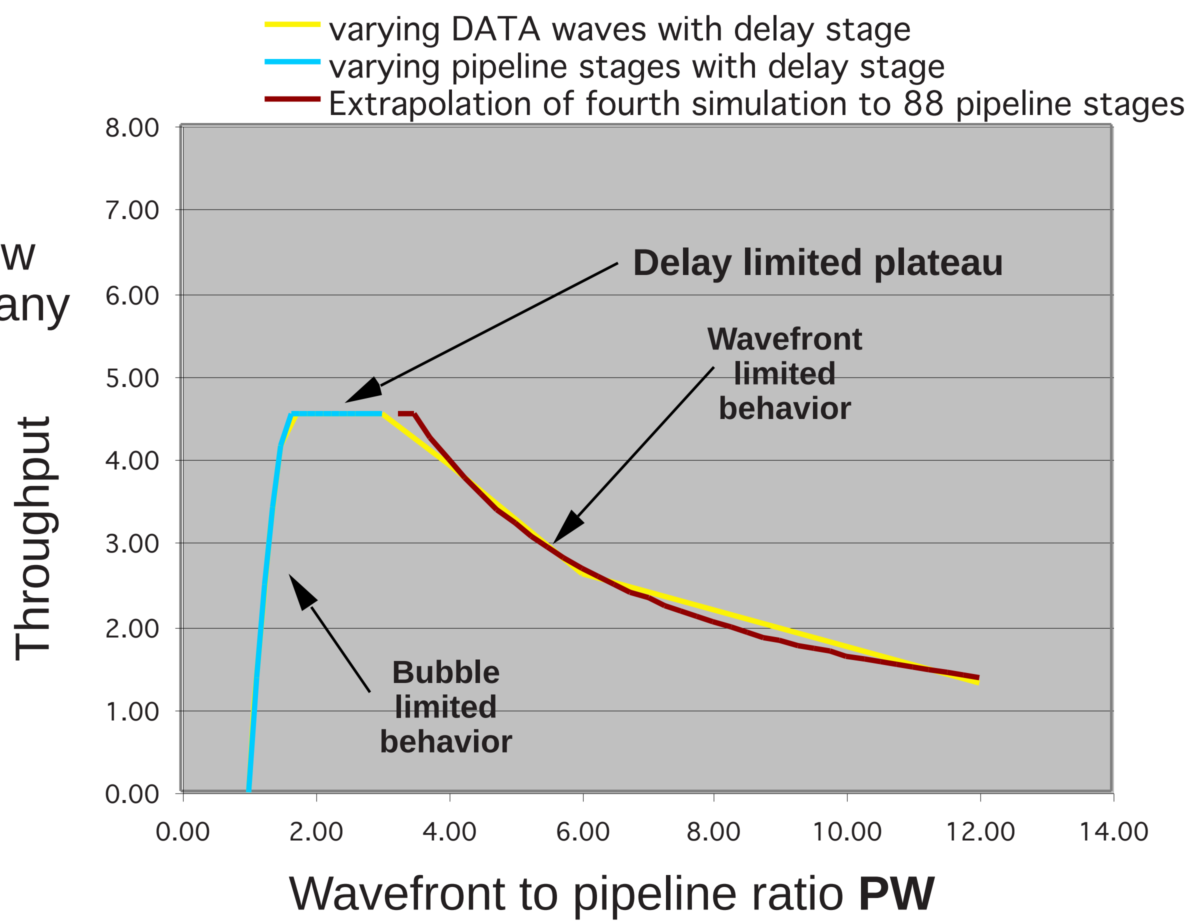
bubble limited

Pipeline Ring Performance

For ring with data path delay in a single stage

The delay limited throughput behavior is the ideal optimal throughput for ring. Wavefronts and bubbles are free flowing through each other with no waiting! The throughput is identical to what a free flowing open pipeline would deliver! The integral nature of the ring does not apply here.

The plateau occurs when there is a slow stage and many fast stages.

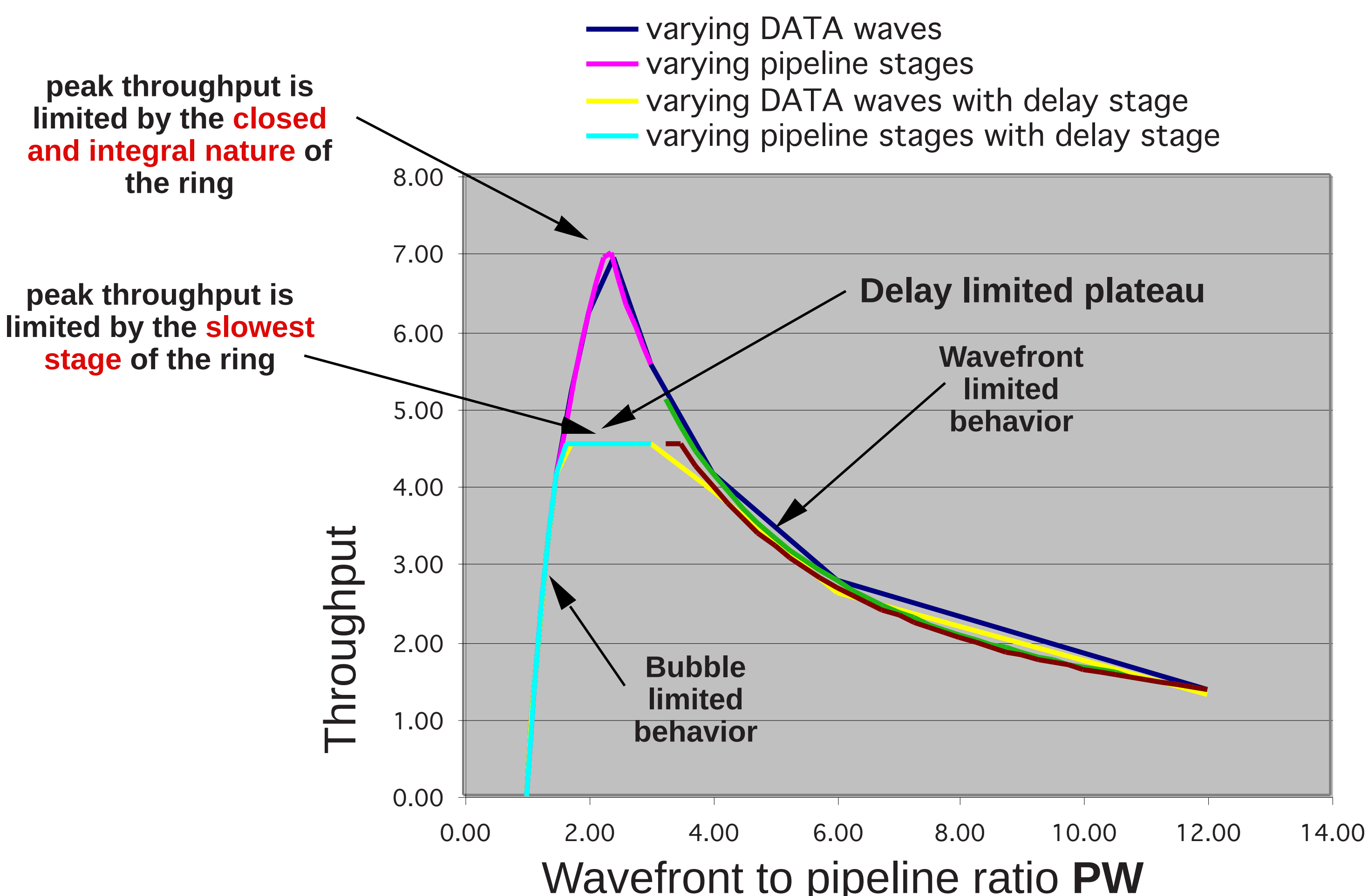


Comparison of Delay Limited Behavior and Non Delay Limited Behavior

Delay limited behavior is the more typical ring behavior to deal with in practical applications.

Peak throughput is achieved with a smaller PW (fewer stages)

There is more leeway in achieving peak throughput



Calculated Ring Studies

We present several studies calculated from basic parameters to provide a broader view of ring behavior.

Each study presents different delay configuration for the ring.

All studies are 24 pipeline stages with varying wavefront populations.

24 Pipeline Stages With Varying DATA Waves
4 Tic Delay in All Stages

Pipeline stages	wave fronts	bubbles	slowest cycle	wavefront population period	wavefront rejoin period	bubble population period	bubble rejoin period	Limit period	Through put /period	Throughput /50 tics	
24	0	24	11	0	168	0	96	0	0	0	
24	2	22	11	22	168	242	96	168	2	0.60	wavefront limited
24	4	20	11	44	168	220	96	168	4	1.19	wavefront limited
24	6	18	11	66	168	198	96	168	6	1.79	wavefront limited
24	8	16	11	88	168	176	96	168	8	2.38	wavefront limited
24	10	14	11	110	168	154	96	168	10	2.98	wavefront limited
24	12	12	11	132	168	132	96	168	12	3.57	wavefront limited
24	14	10	11	154	168	110	96	168	14	4.17	wavefront limited
24	16	8	11	176	168	88	96	96	8	4.17	bubble limited
24	18	6	11	198	168	66	96	96	6	3.13	bubble limited
24	20	4	11	220	168	44	96	96	4	2.08	bubble limited
24	22	2	11	242	168	22	96	96	2	1.04	bubble limited
24	24	0	11	0	168	0	96	0	0	0	

Stage Forward latency = 7 tics
Stage Reverse latency = 4 tics
Slowest cycle time =11 tics
Wavefront rejoin period = 24*7 = 168 tics
Bubble rejoin period = 24*4 = 96 tics

24 Pipeline Stages With Varying DATA Waves
8 Tic Delay in one Stage

Pipeline stages	wave fronts	bubbles	slowest cycle	wavefront population period	wavefront rejoin period	bubble population period	bubble rejoin period	Limit period	Through put /period	Throughput /50 tics	
24	0	24	11	0	80	0	96	0	0	0	
24	2	22	11	30	80	330	96	80	2	1.25	wavefront limited
24	4	20	11	60	80	300	96	80	4	2.50	wavefront limited
24	6	18	11	90	80	270	96	15	1	3.33	delay limited
24	8	16	11	120	80	240	96	15	1	3.33	delay limited
24	10	14	11	150	80	210	96	15	1	3.33	delay limited
24	12	12	11	180	80	180	96	15	1	3.33	delay limited
24	14	10	11	210	80	150	96	15	1	3.33	delay limited
24	16	8	11	240	80	120	96	15	1	3.33	delay limited
24	18	6	11	270	80	90	96	96	6	3.13	bubble limited
24	20	4	11	300	80	60	96	96	4	2.08	bubble limited
24	22	2	11	330	80	30	96	96	2	1.04	bubble limited
24	24	0	11	0	80	0	96	0	0	0	

Stage Forward latency = 3 tics
Stage Reverse latency = 4 tics
Slowest cycle time =15 tics
Wavefront rejoin period = 24*3+8 = 80 tics
Bubble rejoin period = 24*4 = 96 tics

24 Pipeline Stages With Varying DATA Waves
8 Tic Delay in All Stages

Pipeline stages	wave fronts	bubbles	slowest cycle	wavefront population period	wavefront rejoin period	bubble population period	bubble rejoin period	Limit period	Through put /period	Throughput /50 tics
24	0	24	11	0	264	0	96	0	0	0
24	2	22	11	30	264	330	96	264	2	0.38
24	4	20	11	60	264	300	96	264	4	0.76
24	6	18	11	90	264	270	96	264	6	1.14
24	8	16	11	120	264	240	96	264	8	1.52
24	10	14	11	150	264	210	96	264	10	1.89
24	12	12	11	180	264	180	96	264	12	2.27
24	14	10	11	210	264	150	96	264	14	2.65
24	16	8	11	240	264	120	96	264	16	3.03
24	18	6	11	270	264	90	96	96	6	3.13
24	20	4	11	300	264	60	96	96	4	2.08
24	22	2	11	330	264	30	96	96	2	1.04
24	24	0	11	0	264	0	96	0	0	0

wavefront limited

bubble limited

Stage Forward latency = 11 tics
Stage Reverse latency = 4 tics
slowest cycle time =15 tics
Wavefront rejoin period = 24*11 = 264 tics
Bubble rejoin period = 24*4 = 96 tics

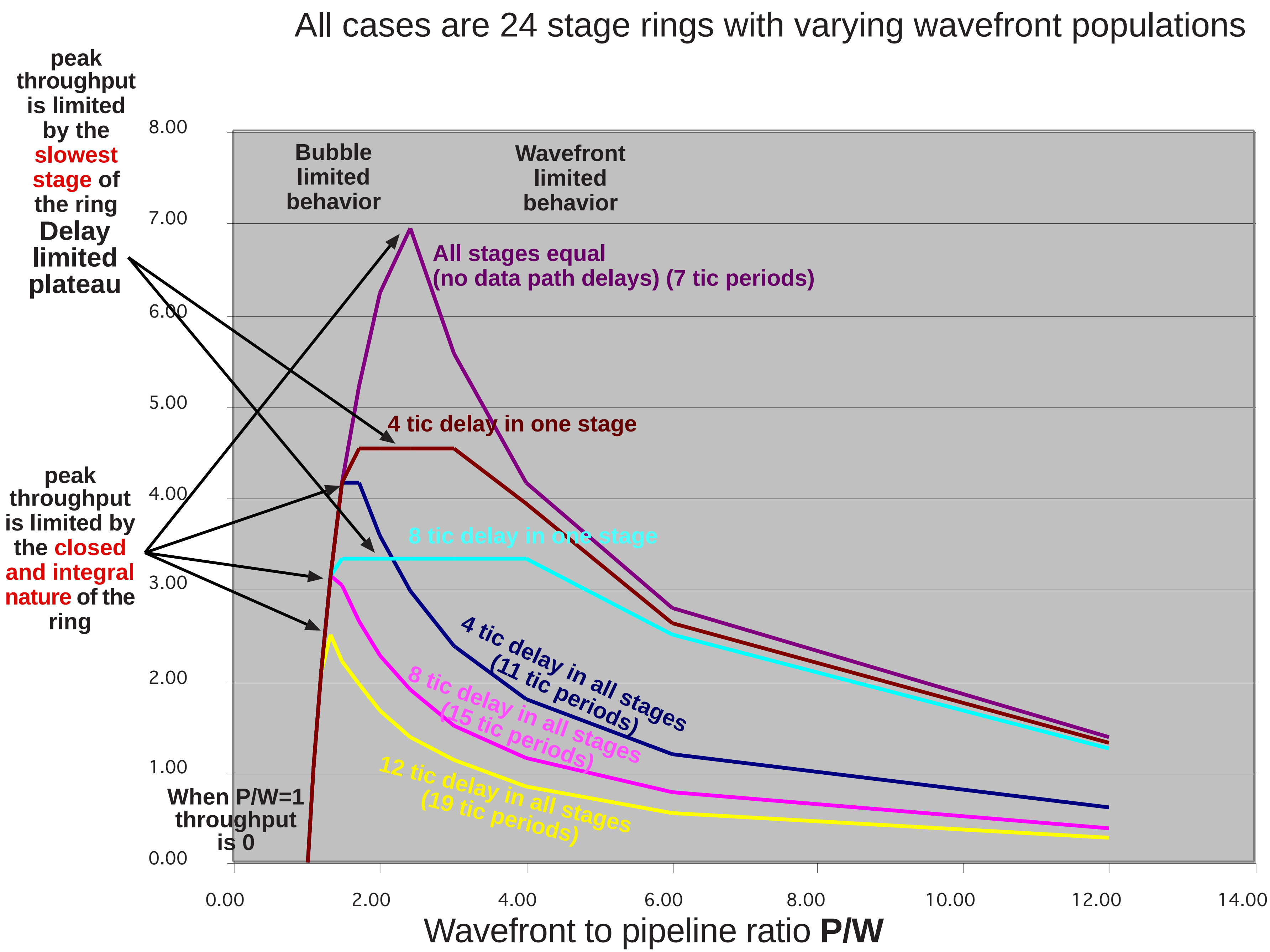
24 Pipeline Stages With Varying DATA Waves

12 Tic Delay in All Stages

Pipeline stages	wave fronts	bubbles	slowest cycle	wavefront population period	wavefront rejoin period	bubble population period	bubble rejoin period	Limit period	Through put /period	Throughput /50 tics	
24	0	24	11	0	360	0	96	0	0	0	
24	2	22	11	38	360	418	96	360	2	0.28	wavefront limited
24	4	20	11	76	360	380	96	360	4	0.56	wavefront limited
24	6	18	11	114	360	342	96	360	6	0.83	wavefront limited
24	8	16	11	152	360	304	96	360	8	1.11	wavefront limited
24	10	14	11	190	360	266	96	360	10	1.39	wavefront limited
24	12	12	11	228	360	228	96	360	12	1.67	wavefront limited
24	14	10	11	266	360	190	96	360	14	1.94	wavefront limited
24	16	8	11	304	360	152	96	360	16	2.22	wavefront limited
24	18	6	11	342	360	114	96	360	18	2.50	wavefront limited
24	20	4	11	380	360	76	96	96	4	2.08	bubble limited
24	22	2	11	418	360	38	96	96	2	1.04	bubble limited
24	24	0	11	0	360	0	96	0	0	0	

Stage Forward latency = 15 tics
Stage Reverse latency = 4 tics
slowest cycle time =19 tics
Wavefront rejoin period = 24*15 = 360 tics
Bubble rejoin period = 24*4 = 96 tics

Overall View of Ring Behavior



As the data path delay grows maximum throughput is achieved with smaller PW

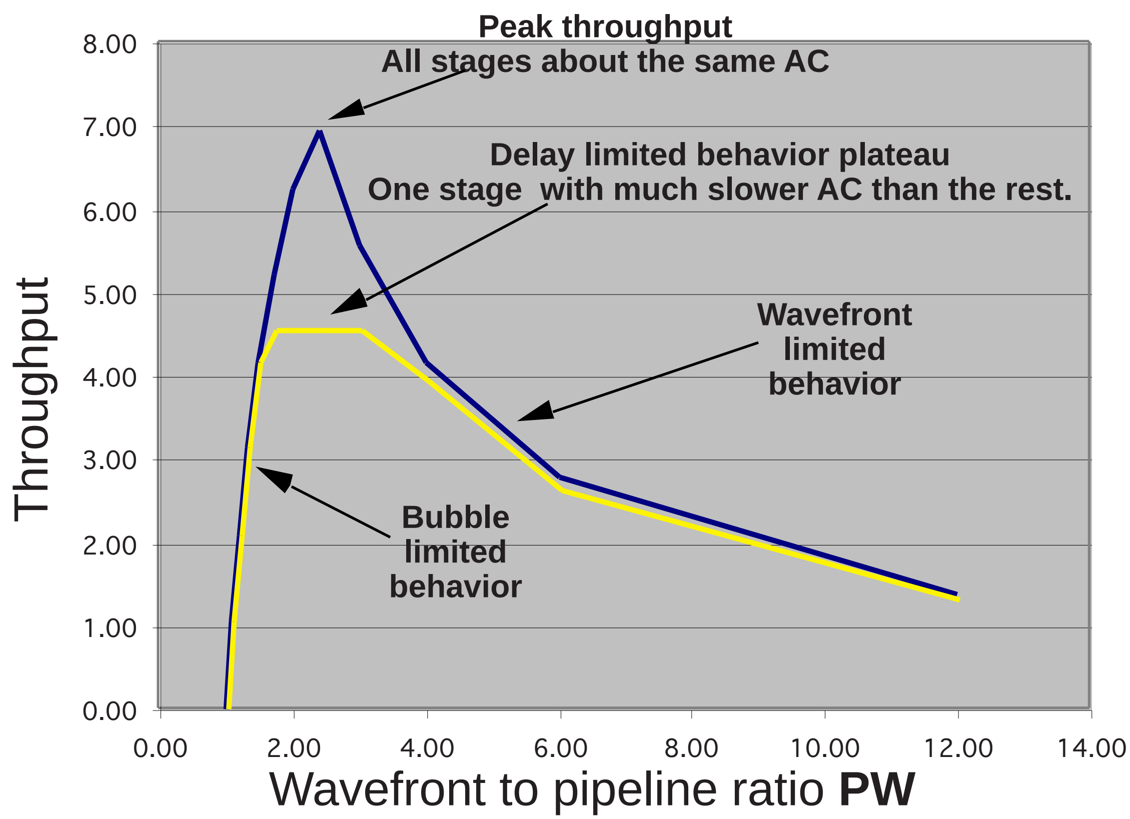
Ring Behavior Relations

The peak throughput for the ring is determined by the slowest cycle period. As the slowest cycle period increases peak throughput decreases and visa versa.

As the wavefront rejoin period increases in relation to the bubble rejoin period, the peak throughput will decrease, meaning that fewer pipeline stages are required for peak throughput in the ring.

As the wavefront rejoin period decreases in relation to the bubble rejoin period, the peak throughput will increase, meaning that more pipeline stages are required for peak throughput in the ring.

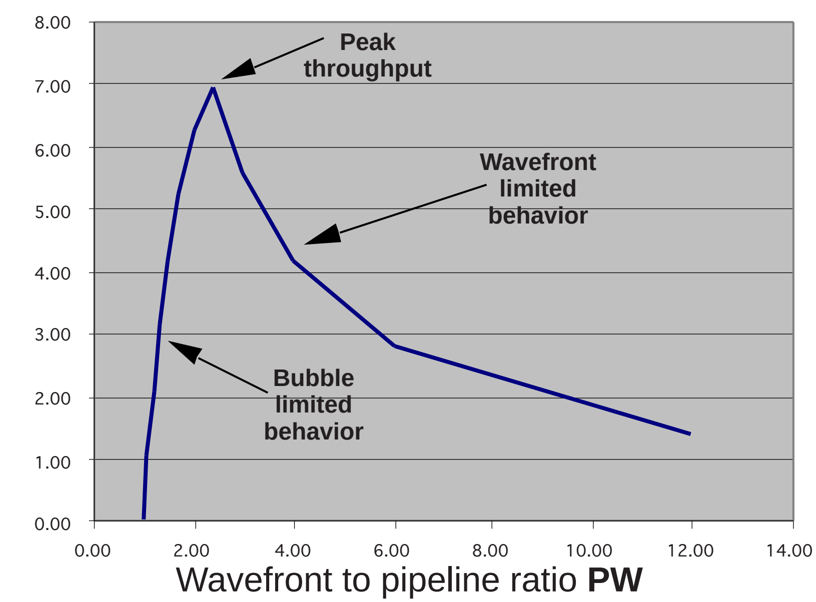
Optimal efficiency occurs with a fast cycle period and with wavefront rejoin period large in relation to bubble rejoin period



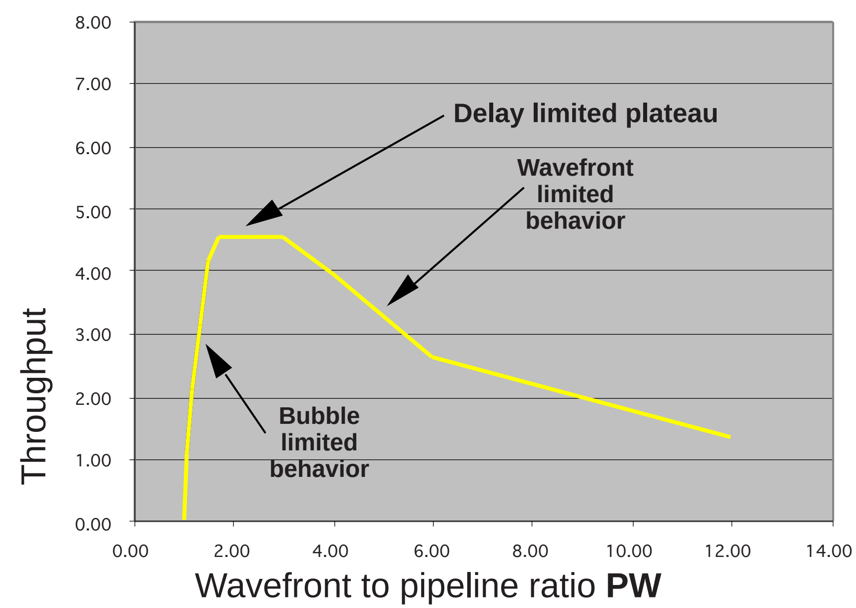
Ring Behavior Relations With Complex Stage Delays

The stage delays in a ring may have varying delay behavior. In this case one must either use average case delay values or try to work directly with the delay distribution functions. There are two basic behavior models.

All stage delays about the same



Few slow stages, many fast stages



If all of the stages have about the same delay characteristic the throughput will vary within a region. Optimal performance will be achieved by tuning the PW of the ring to bring the region of variation to encompass the peak throughput.

If there are a few slow stages and many fast stages the ring will be in delay limited behavior mode and the throughput variation region may be entirely contained on the throughput plateau. The throughput cannot be increased but optimal efficiency will be achieved by tuning the PW of the ring to bring the region of variation to encompass to the left of the plateau.

References to Previous work

The most thorough work on pipeline ring behavior is Ted William's Phd Thesis. He defines wavefronts, bubbles and the pipeline structure itself somewhat differently but the underlying understanding is identical to that presented here.

Williams, Ted. E. "Analyzing and Improving the Latency and Throughput Performance of Self-Timed Pipelines and Rings."1992 IEEE Int. Symp. on Circuits and Systems. Vol. 2, 665 - 668. Also see "Self - Timed Rings and Their Application to Division." Tech. Report No. CSL-TR-91-482, Stanford U. May, 1991.

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