Presentation Slides

Chapter 14

Complex Pipeline Structures

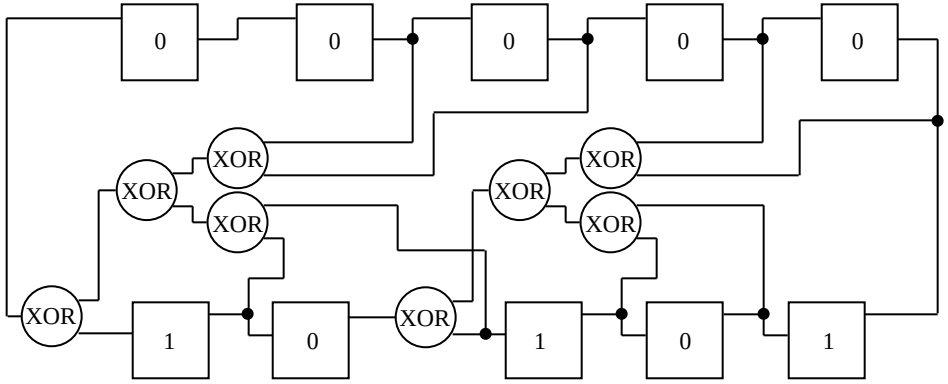
Logically Determined Design:
Clockless System Design With NULL Convention Logic

by Karl Fant

John Wiley & Sons, Inc.

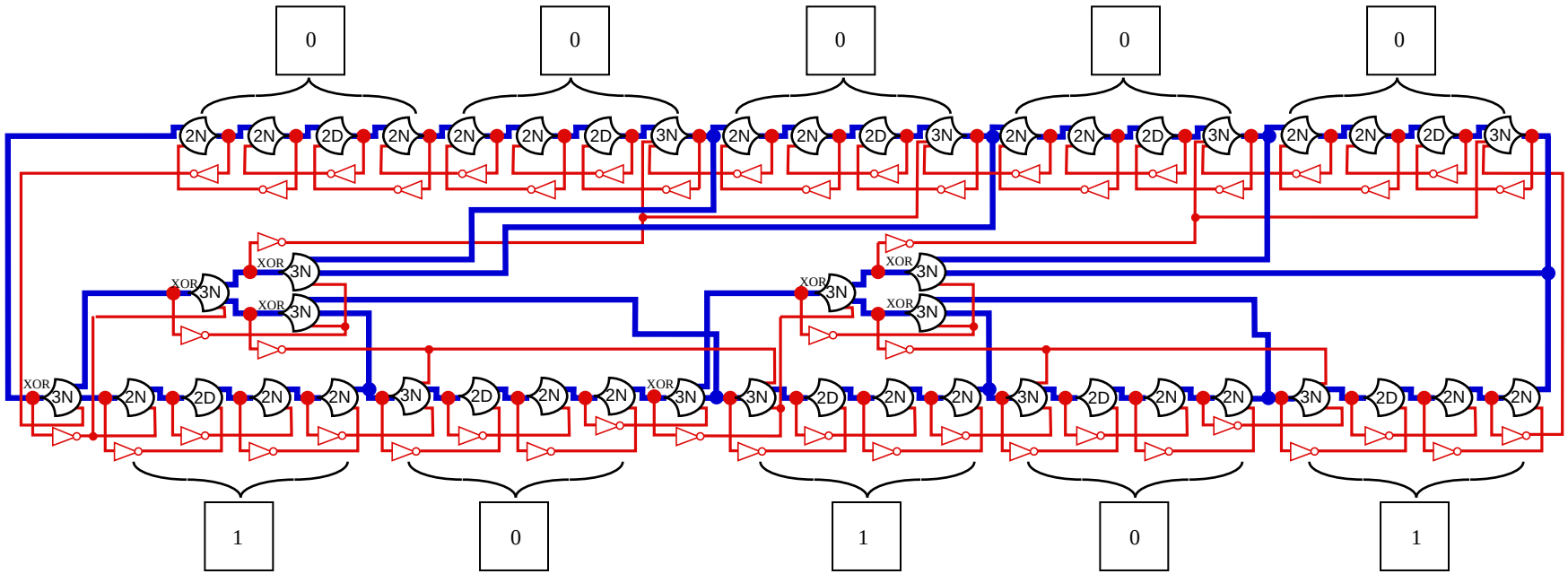
Presents the optimally efficient design of a complex LFSR pipeline structure.

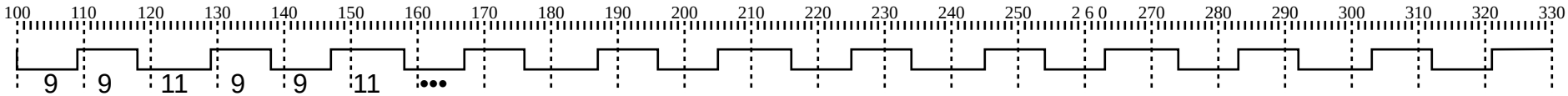
LFSR Model



Initial mapping to 2NCL

Gate level pipelined, collapsed data path model

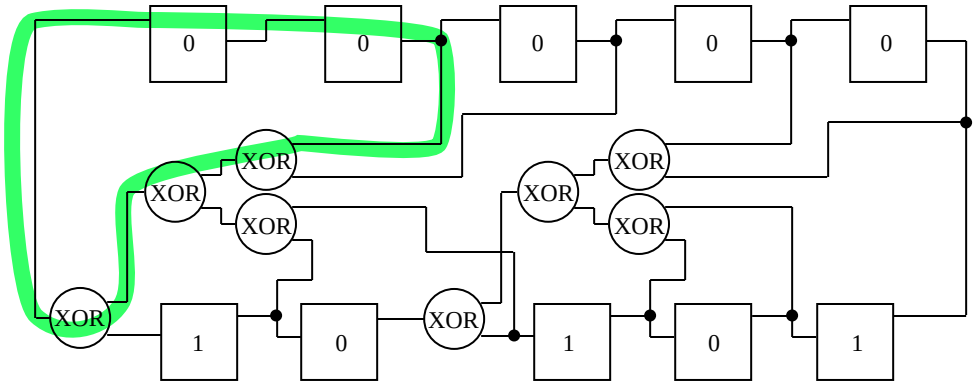




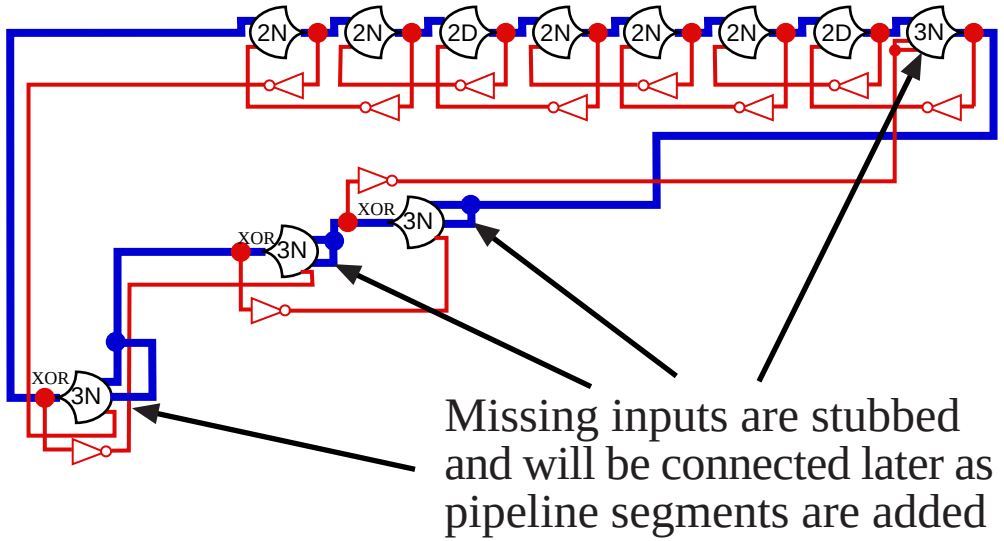
With a repeating cycle period pattern of 9,9,11,... the throughput of the initial mapping is 3 wavefronts every 29 tics or 10.3 wavefronts pre 100 tics.

Step 1

The initial subring

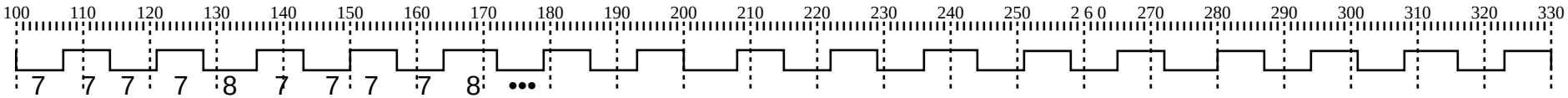


2NCL Subring



Step 1
Behavior analysis

cycles in ring	limiting cycle period	bubbles in ring	bubble population period	bubble rejoin period	wavefronts in ring	wavefront population period	wavefront rejoin period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
14	7	10	70	56	4	28	42	4/42	9.52	Wavefront
13	7	9	63	52	4	28	39	4/39	10.26	Wavefront
12	7	8	56	48	4	28	36	4/36	11.11	Wavefront
11	7	7	49	44	4	28	33	4/33	12.12	Wavefront
10	7	6	42	40	4	28	30	4/30	13.33	Wavefront
9	7	5	35	36	4	28	27	5/36	13.88	Bubble
8	7	4	28	32	4	28	24	4/32	12.5	Bubble
7	7	3	21	28	4	28	21	3/28	10.7	Bubble
6	7	2	14	24	4	28	18	2/24	8.33	Bubble
5	7	1	7	20	4	28	15	1/20	5.0	Bubble



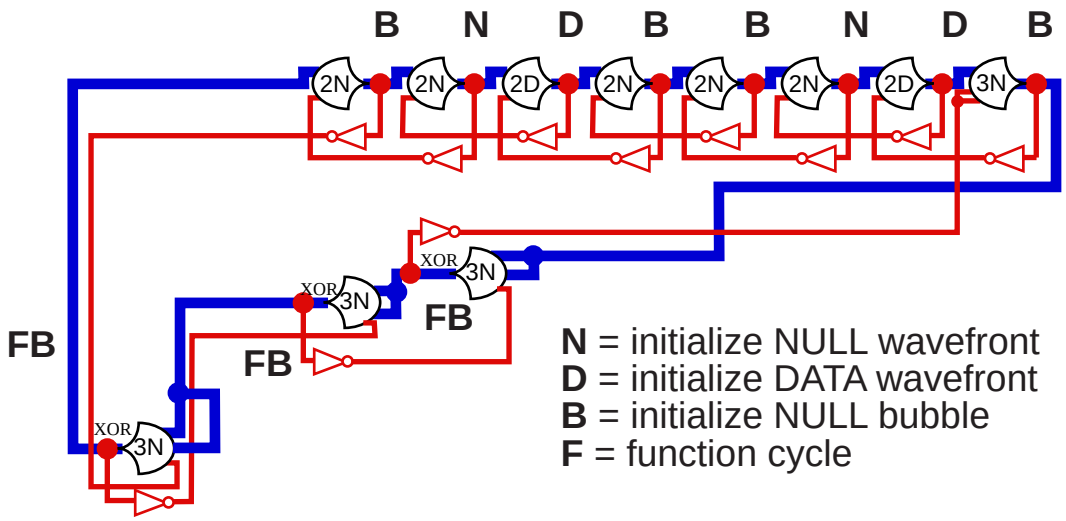
Every cycle in the initial structure has a period of 7 tics so the maximum possible throughput of the structure is 1 wavefront every 7 tics or 14.3 wavefronts per 100 tics

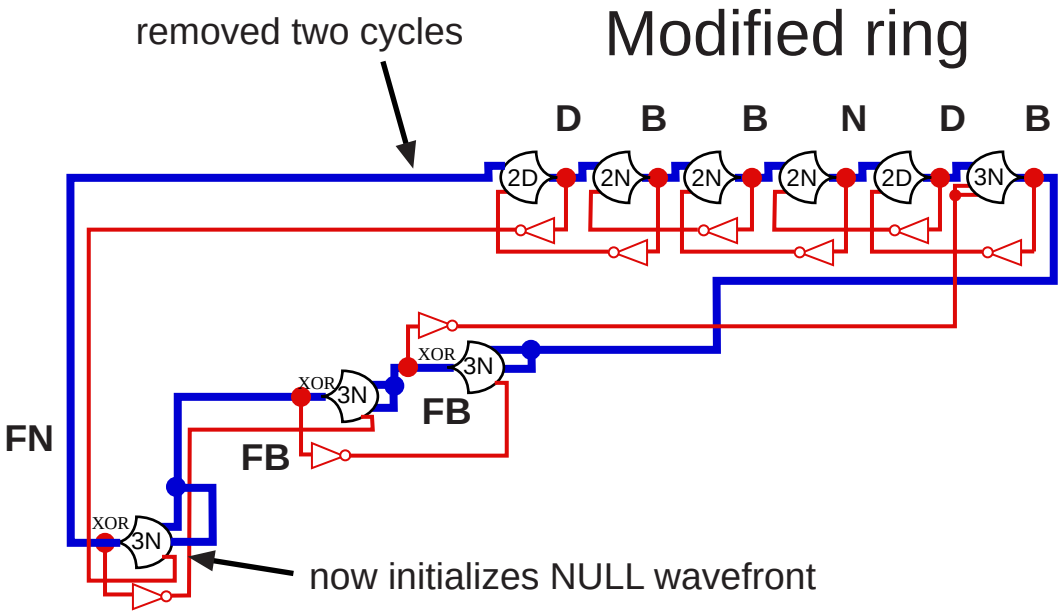
A ring with 9 cycles delivers the optimal throughput performance generating a repeating cycle period pattern of 7,7,7,7,8,... Five wavefronts every 36 tics or 13.88 wavefronts per 100 tics.

The throughput of the initial ring establishes a limit for the structure.

It is already established that one wavefront every 7 tics cannot be achieved.

Step 1
Ring Modification





The critical cycles in a pipeline expression are the functional cycles and the cycles that initialize a DATA wavefront. These cannot be removed.

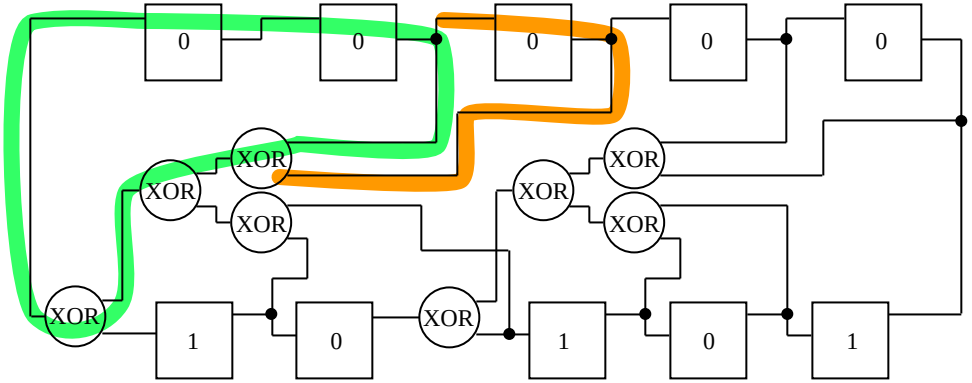
A cycle initialized to NULL immediately prior to a cycle initializing a DATA wavefront initializes the NULL wavefront associated with the data wavefront. A cycle initializing a NULL wavefront can be removed if another cycle assumes the responsibility of initializing the NULL wavefront.

Any non-function cycle initializing a bubble can be removed. These are loosely referred to as buffer cycles. Non-function cycles initializing a bubble (buffer cycles) can be freely added to a pipeline structure.

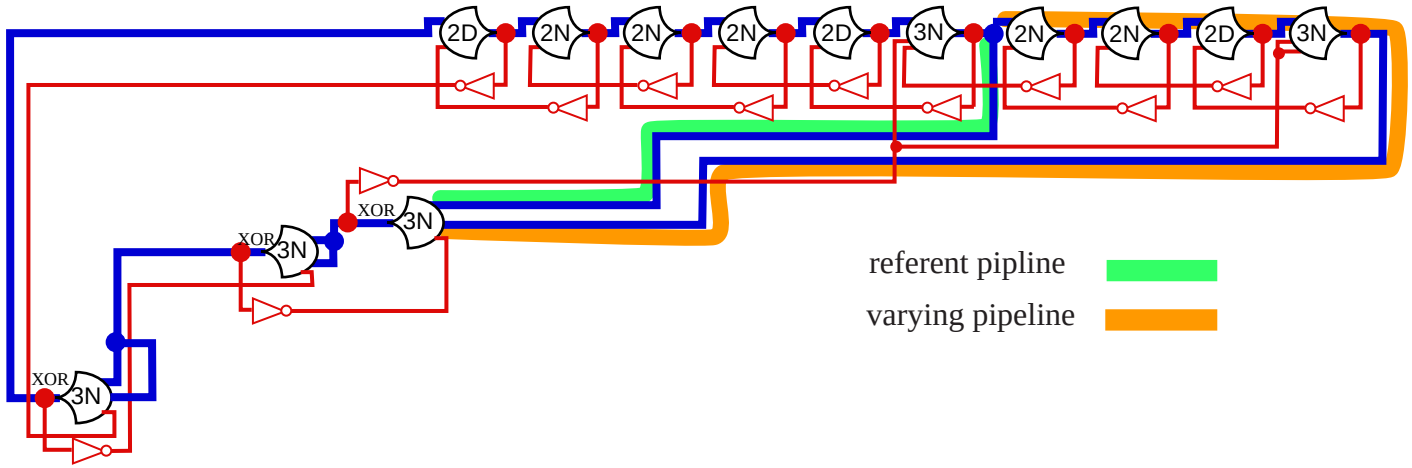
In this case the two leftmost cycles on the top rank will be removed to make the ring a 9 cycle ring. The leftmost XOR cycle assumes the responsibility of initializing the NULL wavefront.

Step 2

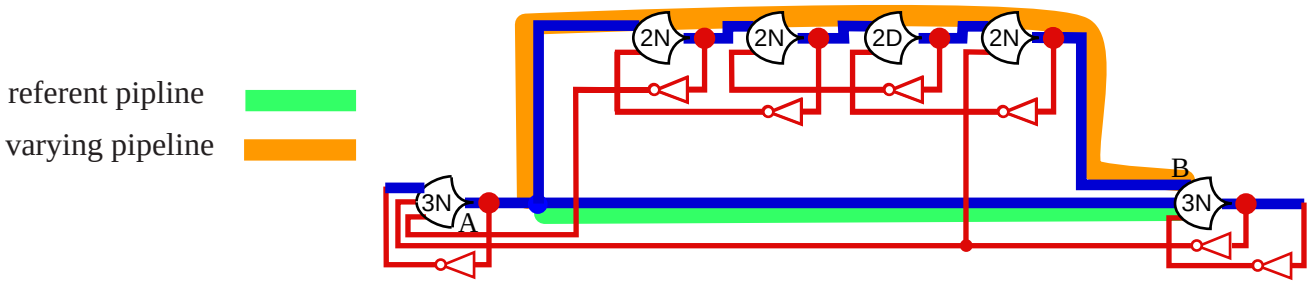
Specification graft model



2NCL graft model



Step 2
Isolation model

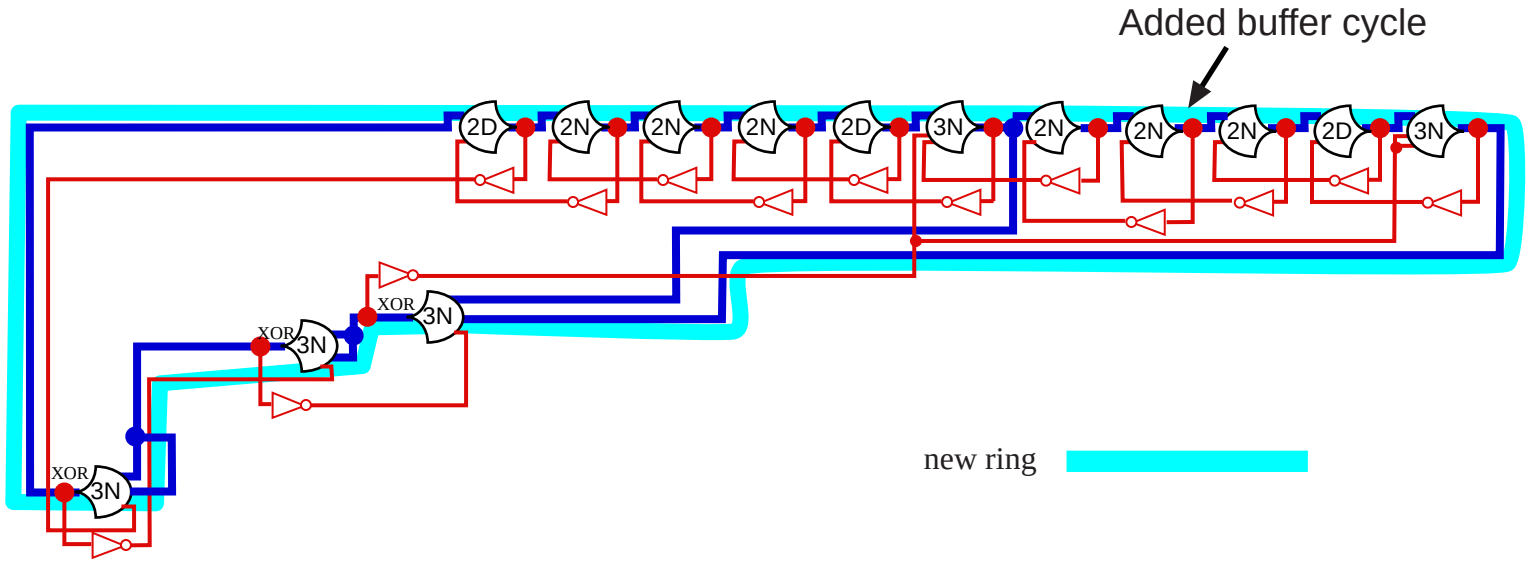


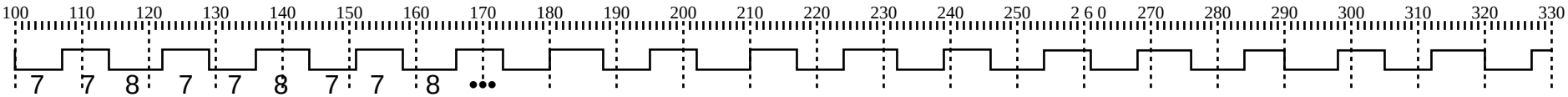
cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	15	1/15	6.66	renewal
4	7	14	19	2/19	10.52	renewal
5	7	21	23	3/23	13.04	renewal
6	7	21	22	3/22	13.64	renewal
7	7	21	25	3/25	12.00	renewal
8	7	21	28	3/28	10.71	renewal
9	7	21	31	3/31	9.68	renewal
10	7	21	34	3/34	8.82	renewal

The isolation model analysis indicates that maximal throughput is achieved with six cycles in the graft pipeline segment. There are currently five cycles in the graft pipeline so one cycle will be added by adding a buffer cycle.

The throughput of three wavefronts every 22 tics or 13.64 wavefronts per 100 tics is less than the ring throughput and establishes a new throughput limit for the structure.

Step 2
Modified structure





The new pipeline structure delivers a repeating cycle period pattern of 7,7,8,... three wavefronts every 22 tics or 13.64 wavefronts per 100 tics.

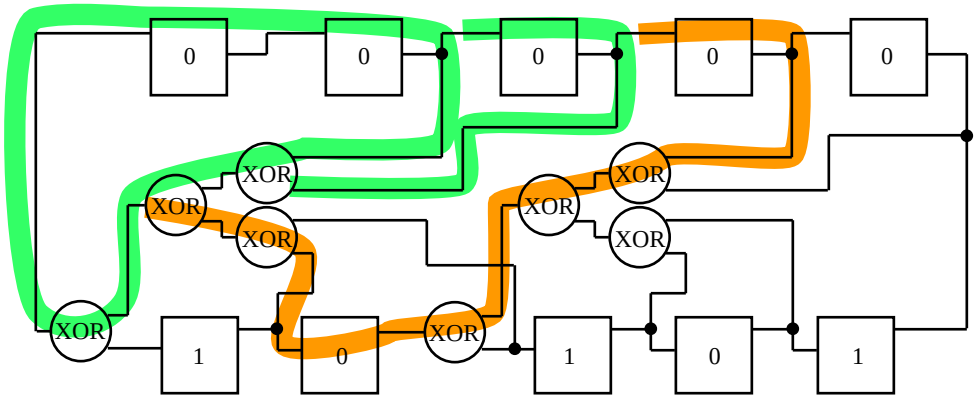
New ring performance

		Population period	Rejoin period	Limiting behavior mode
cycles	14			
wavefronts	6	42	42	
bubbles	8	56	56	

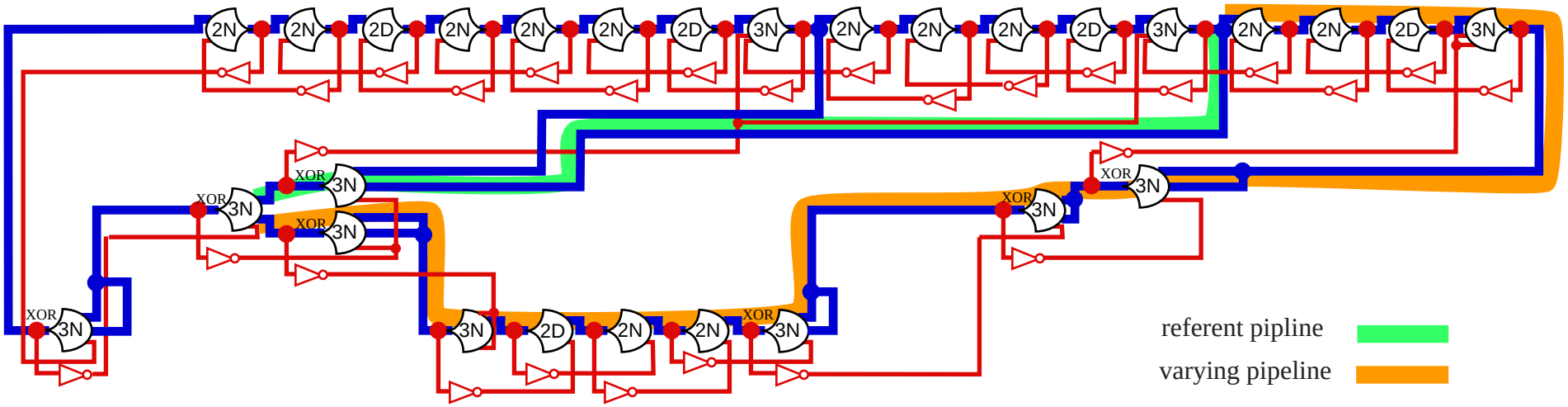
The new ring is perfectly balanced and does not limit the throughput of the new structure.

Step 3

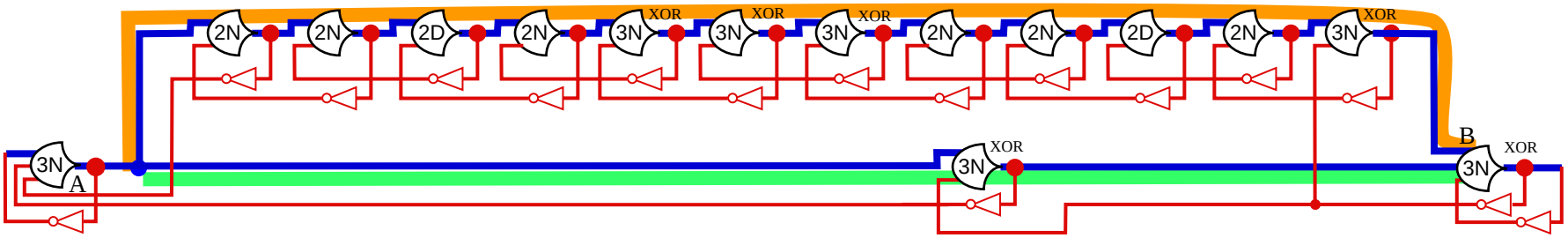
Specification graft model



2NCL graft model



Step 3
Isolation model

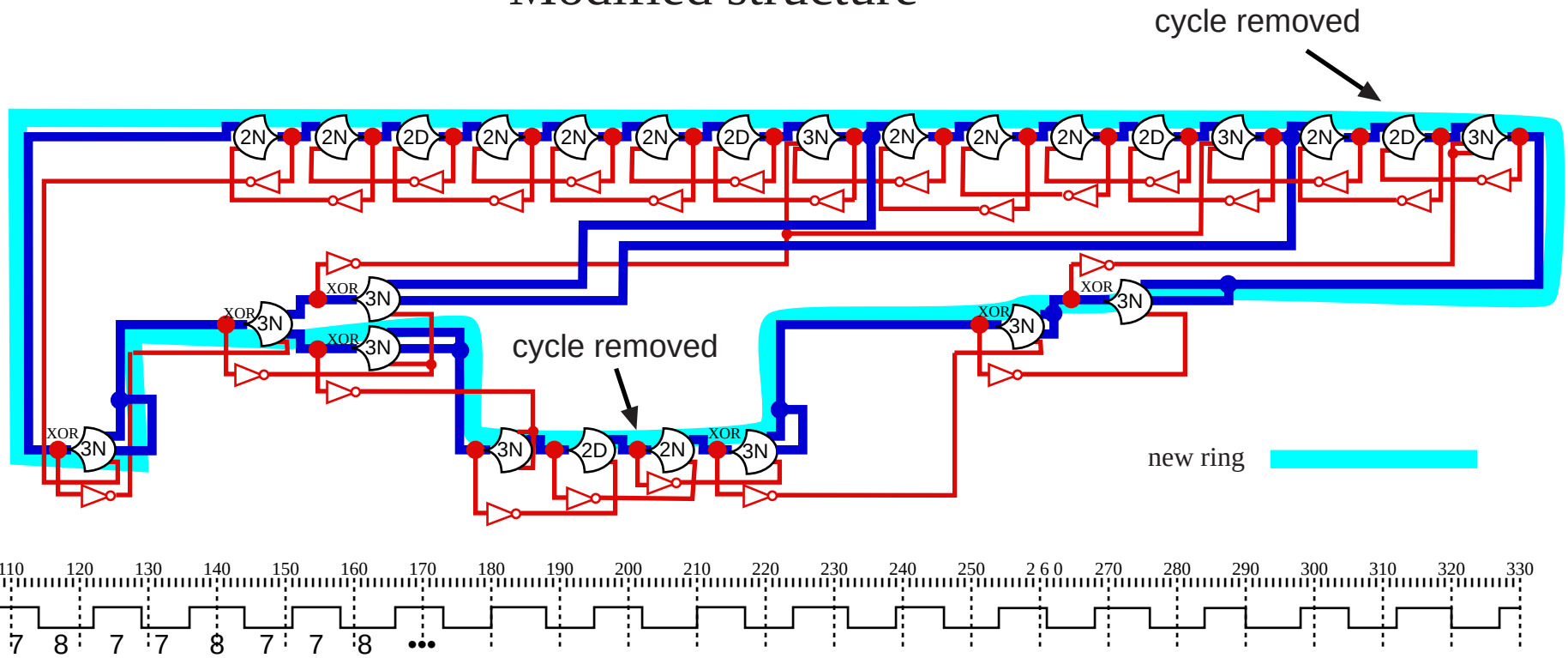


cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
7	7	21	34	3/34	8.82	renewal
8	7	28	38	4/38	10.53	renewal
9	7	35	42	5/42	11.90	renewal
10	7	42	46	6/46	13.04	renewal
11	7	49	50	7/50	14.00	renewal
12	7	42	44	6/44	13.63	renewal
13	7	42	47	6/47	12.76	renewal

The isolation model analysis indicates that maximal throughput is achieved with eleven cycles in the graft pipeline segment. The throughput is greater than the already established limit for the LFSR structure and does not further limit its throughput which remains 13.64 wavefronts per 100 tics.

There are currently thirteen cycles in the graft pipeline so two cycles will be removed. While the cycles can be removed from anywhere in the pipeline segment one cycle will be removed from each end which corresponds to the upper LFSR and the lower LFSR. This flexibility of configuration will be noted and may be useful later.

Step 3
Modified structure



The new pipeline structure still delivers a repeating cycle period pattern of 7,7,8,... three wavefronts every 22 tics or 13.64 wavefronts per 100 tics.

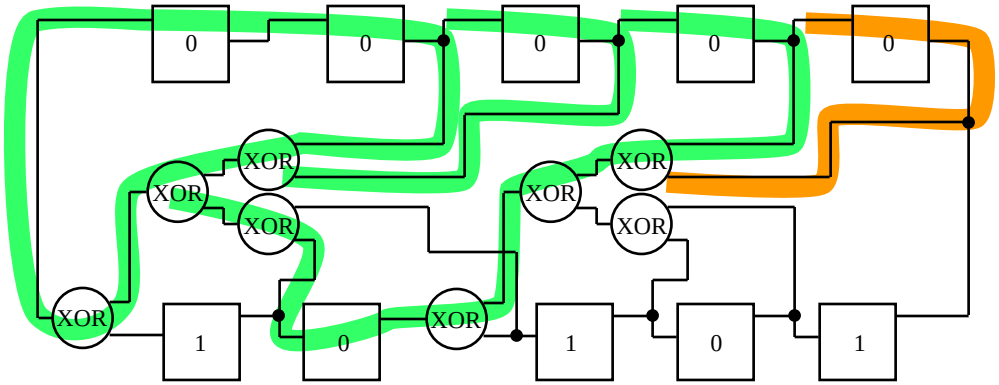
New ring performance

		Population period	Rejoin period	Limiting behavior mode
cycles	23			
wavefronts	10	70	69	
bubbles	13	91	92	bubble

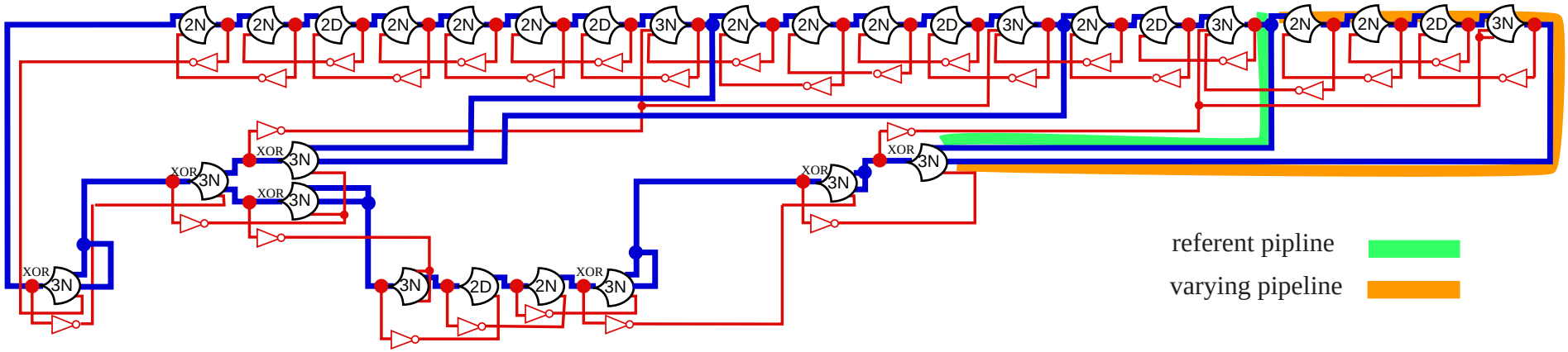
The new ring is slightly bubble limited delivering 13 wavefront every 92 tics or 14.13 wavefronts per hundred tics. This is greater than the current limit of 13.64 wavefronts per 100 tics and does not further limit the throughput of the LFSR structure.

Step 4

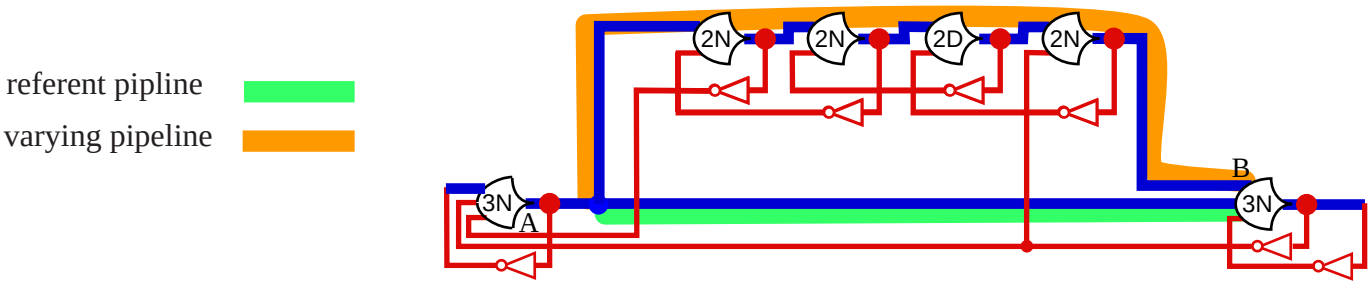
Specification graft model



2NCL graft model



Step 4
Isolation model



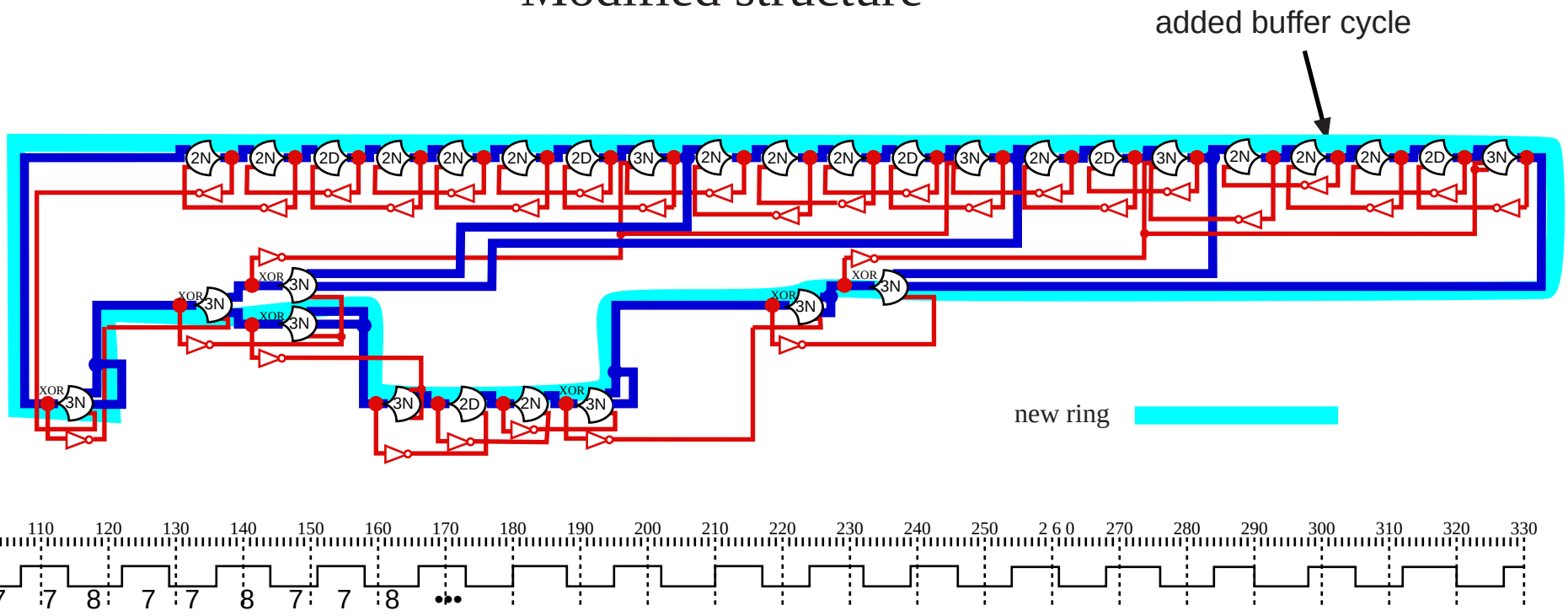
cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	15	1/15	6.66	renewal
4	7	14	19	2/19	10.52	renewal
5	7	21	23	3/23	13.04	renewal
6	7	21	22	3/22	13.64	renewal
7	7	21	25	3/25	12.00	renewal
8	7	21	28	3/28	10.71	renewal
9	7	21	31	3/31	9.68	renewal
10	7	21	34	3/34	8.82	renewal

The step 4 isolation model is identical to the step 2 isolation model and the throughput analysis indicates that maximal throughput is achieved with six cycles in the graft pipeline segment. There are currently five cycles in the graft pipeline so one cycle will be added by adding a buffer cycle.

The throughput is identical to step 2 and does not further limit the throughput of the LFSR structure which remains 13.64 wavefronts per 100 tics.

Step 4

Modified structure



The new pipeline structure still delivers a repreating cycle period pattern of 7,7,8,... three wavefronts every 22 tics or 13.64 wavefronts per 100 tics.

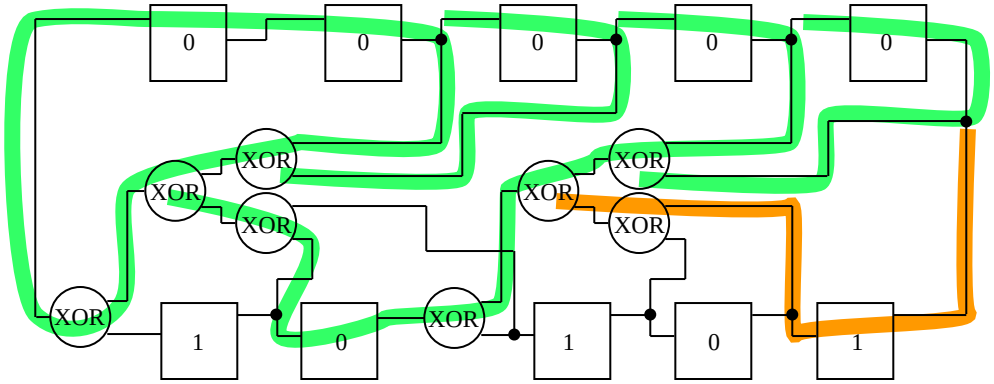
New ring performance

		Population period	Rejoin period	Limiting behavior mode
cycles	28			
wavefronts	12	84	84	
bubbles	16	112	112	

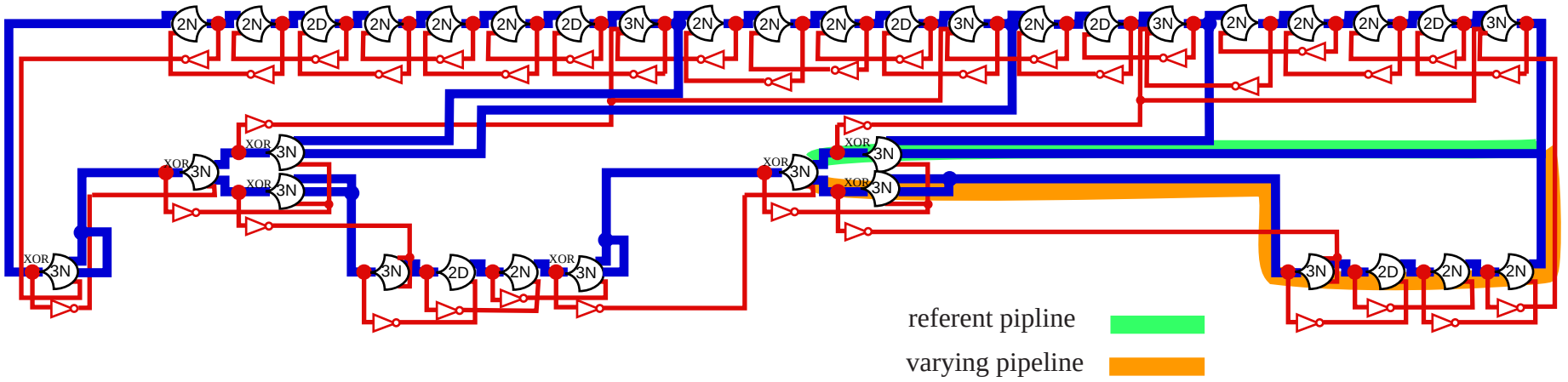
The new ring is perfectly balanced and does not present any throughput limitation.

Step 5

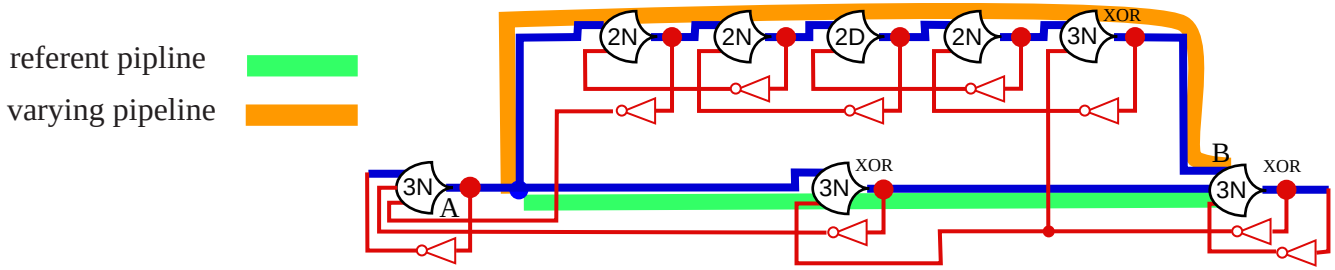
Specification graft model



2NCL graft model



Step 5
Isolation model

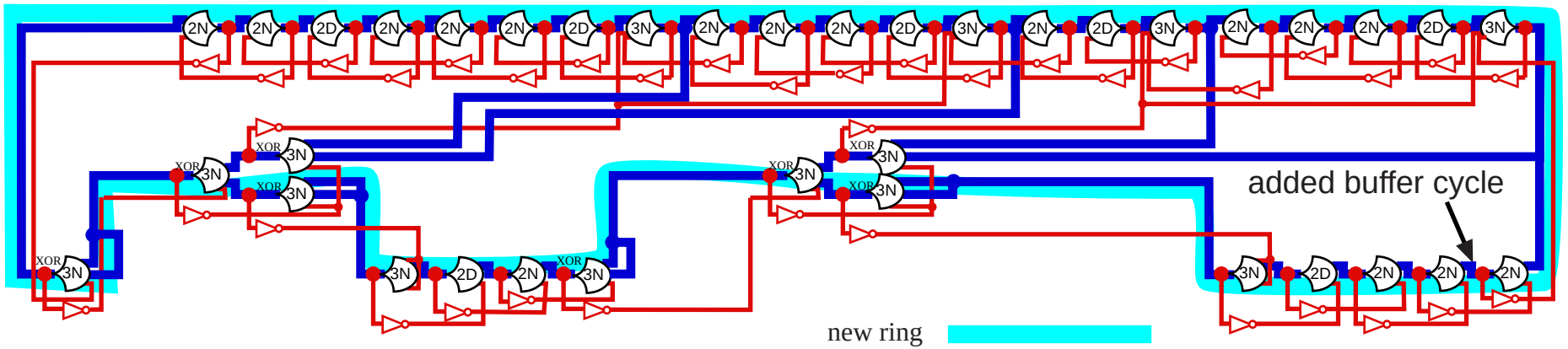


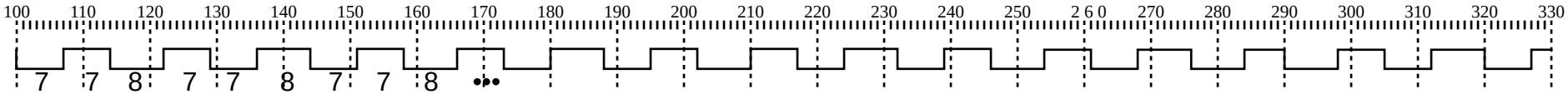
cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	10	18	1/18	4.16	renewal
4	7	20	22	2/22	9.09	renewal
5	7	30	26	3/26	11.54	renewal
6	7	40	30	4/30	13.33	renewal
7	7	40	29	4/29	13.79	renewal
8	7	40	32	4/32	12.50	renewal
9	7	40	35	4/35	11.43	renewal

The isolation model analysis indicates that maximal throughput is achieved with seven cycles in the graft pipeline segment. The throughput is greater than the already established limit for the LFSR structure and does not further limit its throughput which remains 13.64 wavefronts per 100 tics.

There are currently six cycles in the graft pipeline so one buffer cycle will be added.

Step 5
Modified structure





The new pipeline structure still delivers a repeating cycle period pattern of 7,7,8,... three wavefronts every 22 tics or 13.64 wavefronts per 100 tics.

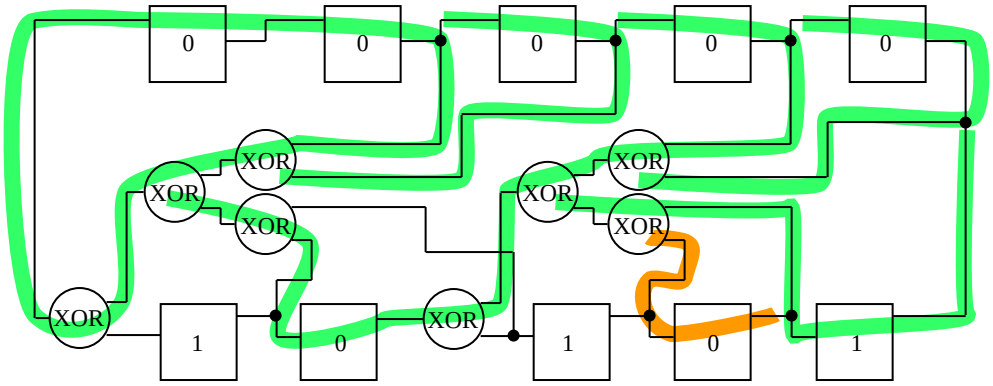
New ring performance

		Population period	Rejoin period	Limiting behavior mode
cycles	33			
wavefronts	14	98	99	wavefront
bubbles	19	133	132	

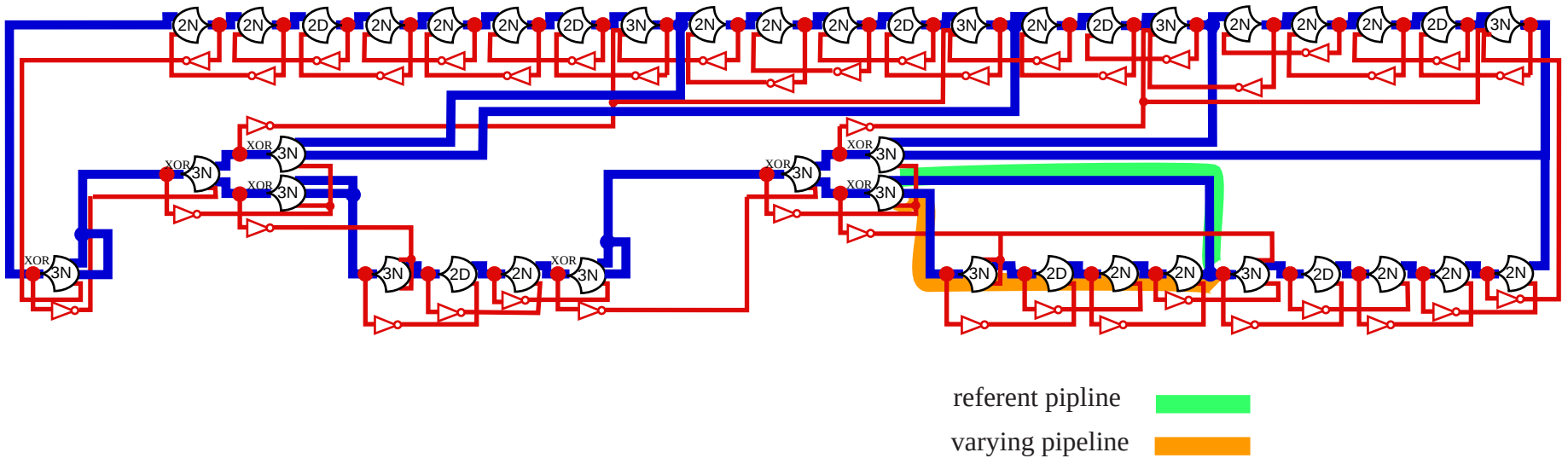
The new ring is slightly wavefront limited delivering 14 wavefront every 99 tics or 14.14 wavefronts per hundred tics. This is greater than the current limit of 13.64 wavefronts per 100 tics and does not further limit the throughput of the LFSR structure.

Step 6

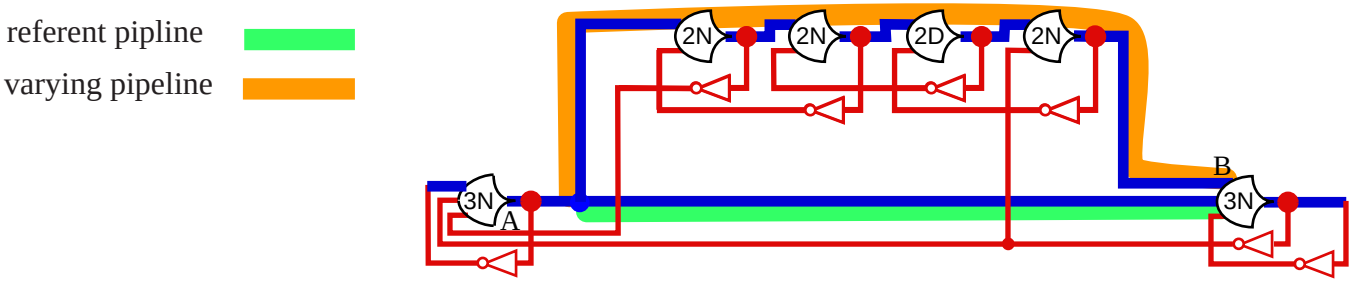
Specification graft model



2NCL graft model



Step 6
Isolation model

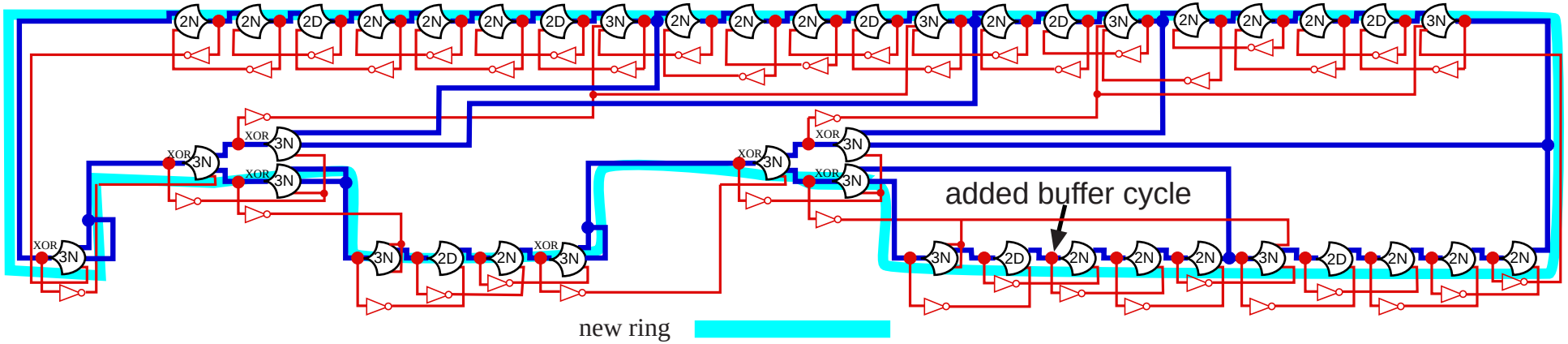


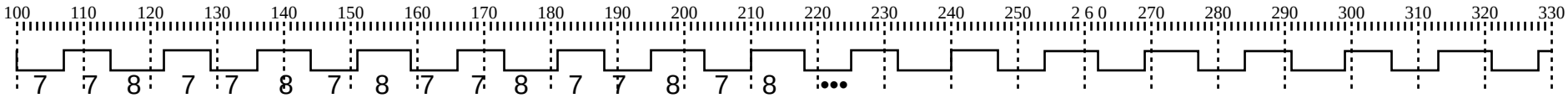
cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	15	1/15	6.66	renewal
4	7	14	19	2/19	10.52	renewal
5	7	21	23	3/23	13.04	renewal
6	7	21	22	3/22	13.64	renewal
7	7	21	25	3/25	12.00	renewal
8	7	21	28	3/28	10.71	renewal
9	7	21	31	3/31	9.68	renewal
10	7	21	34	3/34	8.82	renewal

The step 4 isolation model is identical to the step 2 isolation model and the throughput analysis indicates that maximal throughput is achieved with six cycles in the graft pipeline segment. There are currently five cycles in the graft pipeline so one cycle will be added by adding a buffer cycle.

The throughput is identical to step 2 and does not further limit the throughput of the LFSR structure which remains 13.64 wavefronts per 100 tics.

Step 6
Modified structure





The new pipeline structure does not quite deliver the expected throughput. Jitter among the four inputs of the middle XOR gates affects the throughput. The new structure delivers a repeating cycle period pattern of 7,7,8,7,7,8,7,8,... eight wavefronts every 59 tics or 13.56 wavefronts per 100 tics. This simulation result is accepted as a new throughput limit.

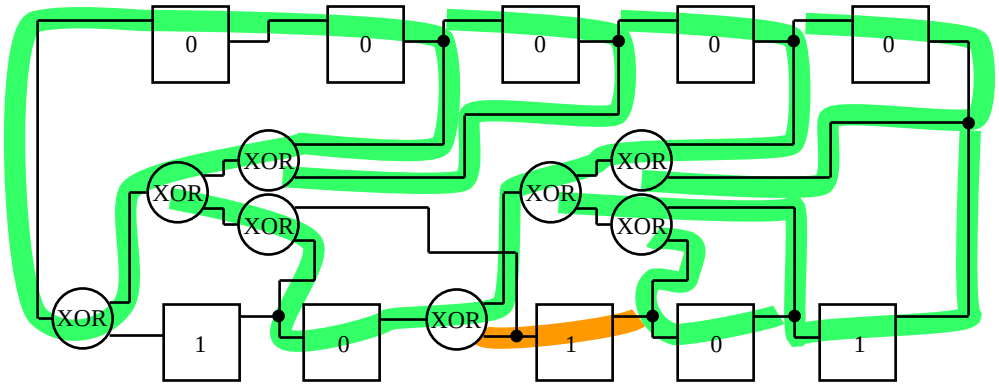
New ring performance

		Population period	Rejoin period	Limiting behavior mode
cycles	38			
wavefronts	16	112	114	wavefront
bubbles	22	154	152	

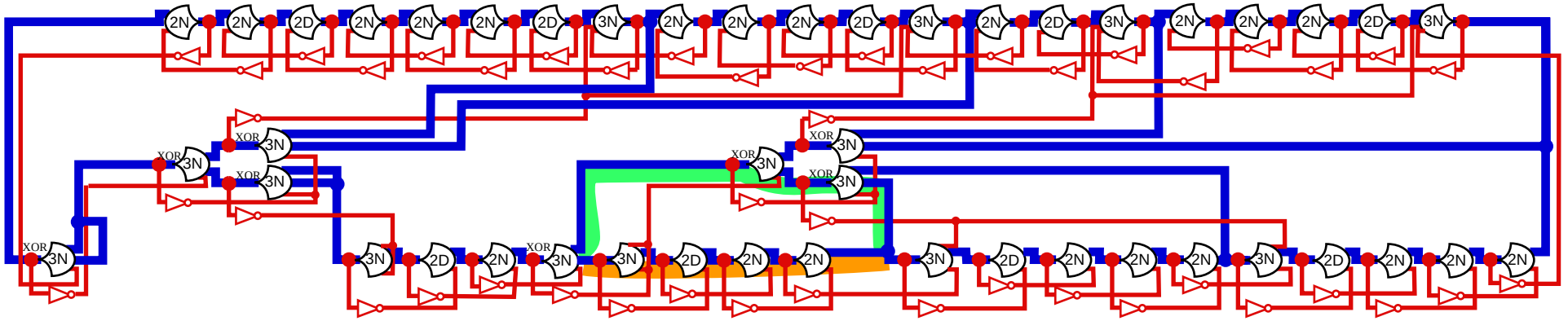
The new ring is slightly wavefront limited delivering 16 wavefronts every 114 tics or 14.03 wavefronts per hundred tics. This is greater than the current limit of 13.56 wavefronts per 100 tics and does not further limit the throughput of the LFSR structure.

Step 7

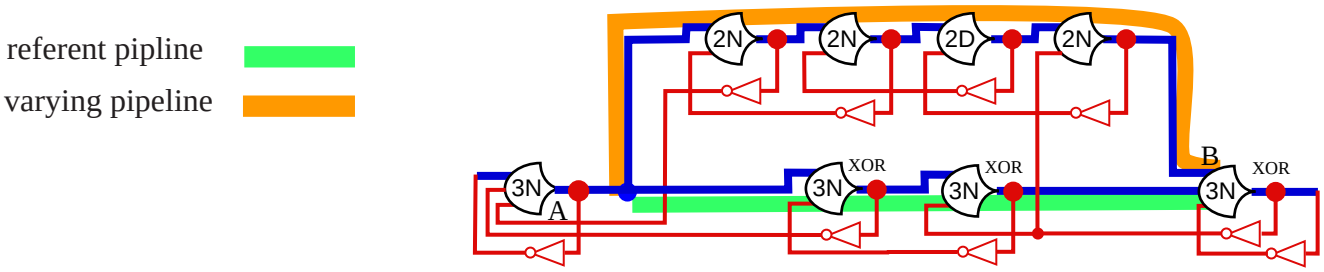
Specification graft model



2NCL graft model



Step 7
Isolation model



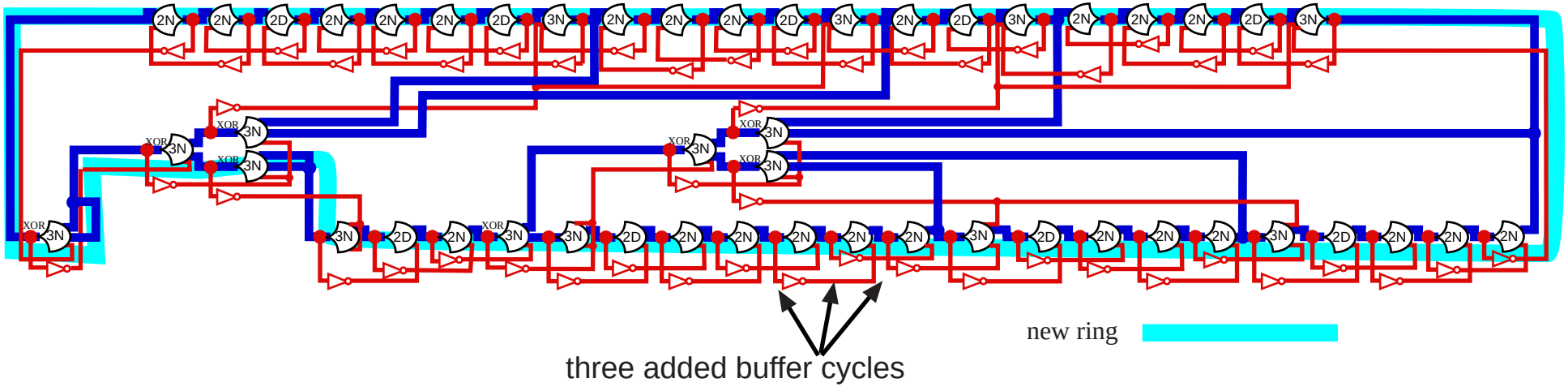
cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	21	1/21	4.76	renewal
4	7	14	25	2/25	8.00	renewal
5	7	21	29	3/29	10.34	renewal
6	7	28	33	4/33	12.12	renewal
7	7	35	37	5/37	13.51	renewal
8	7	35	36	5/36	13.89	renewal
9	7	35	39	5/39	12.82	renewal
10	7	35	42	5/42	11.90	renewal

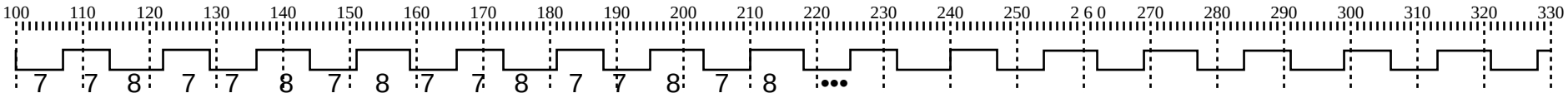
The isolation model analysis indicates that maximal throughput is achieved with eight cycles in the graft pipeline segment.

The throughput is greater than the already established limit for the LFSR structure and does not further limit its throughput which remains 13.56 wavefronts per 100 tics.

There are currently five cycles in the graft pipeline so three buffer cycles will be added.

Step 7
Modified structure





The new pipeline structure still delivers a repeating cycle period pattern of 7,7,8,7,7,8,7,8,...
eight wavefronts every 59 tics or 13.56 wavefronts per 100 tics.

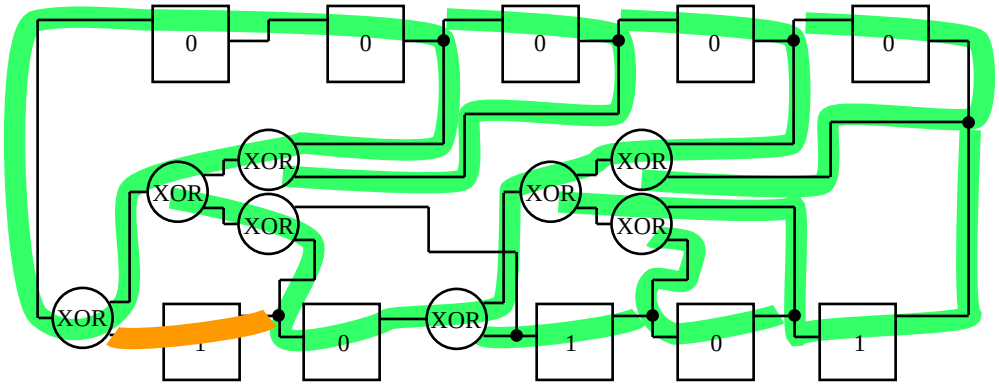
New ring performance

		Population period	Rejoin period	Limiting behavior mode
cycles	43			
wavefronts	18	126	129	wavefront
bubbles	25	175	172	

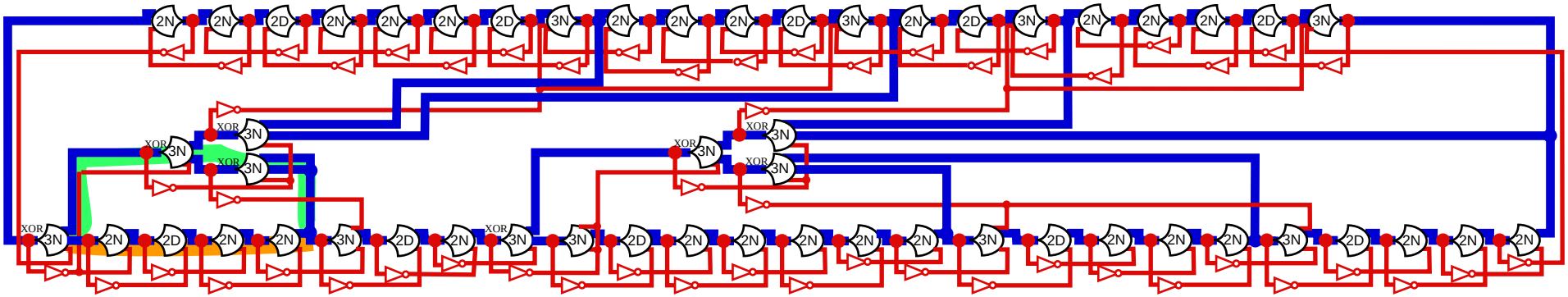
The new ring is slightly wavefront limited delivering 18 wavefront every 129 tics or 13.95 wavefronts per hundred tics. This is greater than the current limit of 13.56 wavefronts per 100 tics and does not further limit the throughput of the LFSR structure.

Step 8

Specification graft model



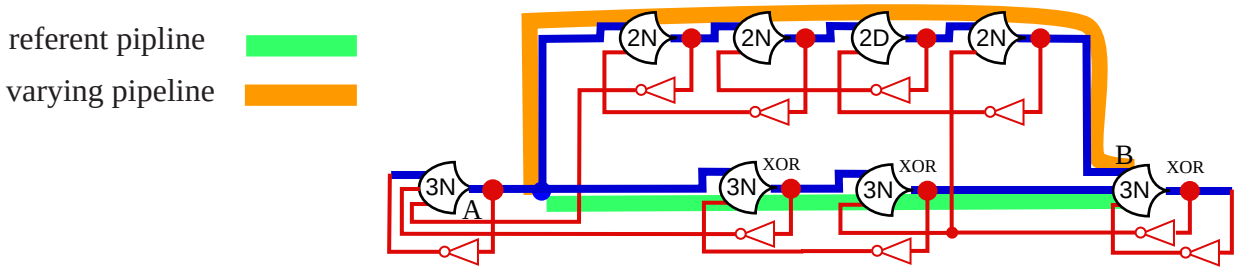
2NCL graft model



referent pipline

varying pipeline

Step 8
Isolation model



cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	21	1/21	4.76	renewal
4	7	14	25	2/25	8.00	renewal
5	7	21	29	3/29	10.34	renewal
6	7	28	33	4/33	12.12	renewal
7	7	35	37	5/37	13.51	renewal
8	7	35	36	5/36	13.89	renewal
9	7	35	39	5/39	12.82	renewal
10	7	35	42	5/42	11.90	renewal

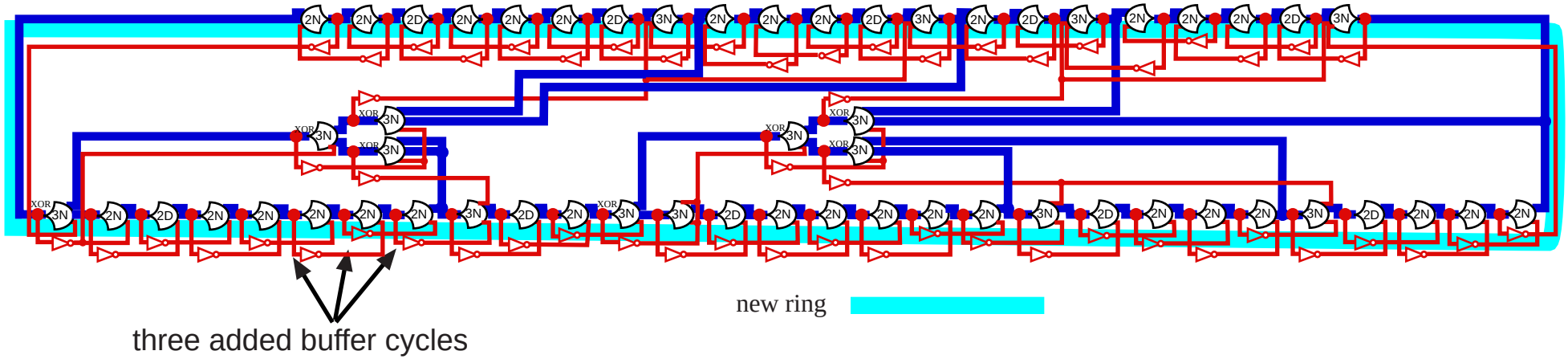
The isolation model analysis indicates that maximal throughput is achieved with eight cycles in the graft pipeline segment.

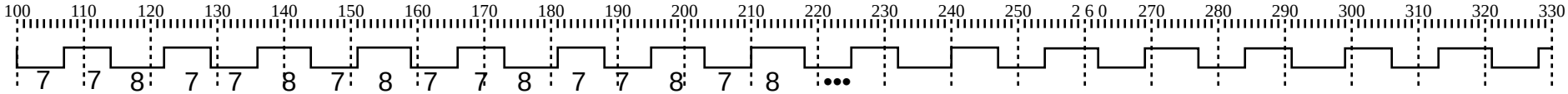
The throughput is greater than the already established limit for the LFSR structure and does not further limit its throughput which remains 13.56 wavefronts per 100 tics.

There are currently five cycles in the graft pipeline so three buffer cycles will be added.

Step 8

Modified structure





The new pipeline structure still delivers a repeating cycle period pattern of 7,7,8,7,7,8,7,8,... eight wavefronts every 59 tics or 13.56 wavefronts per 100 tics.

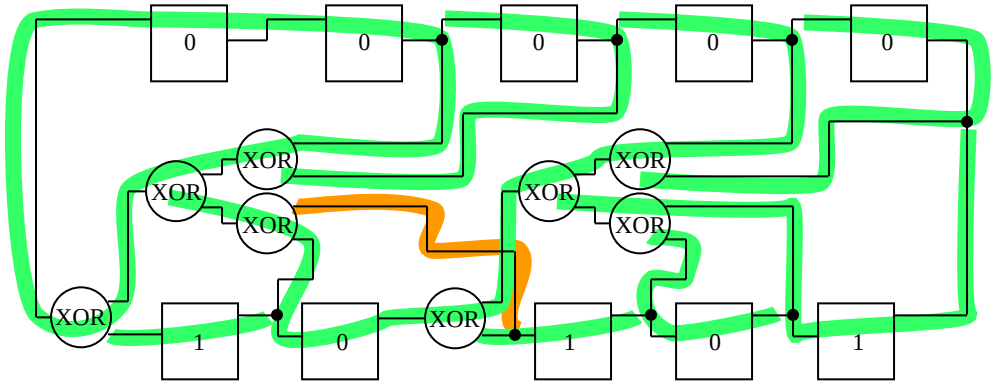
New ring performance

		Population period	Rejoin period	Limiting behavior mode
cycles	48			
wavefronts	20	140	144	wavefront
bubbles	28	196	192	

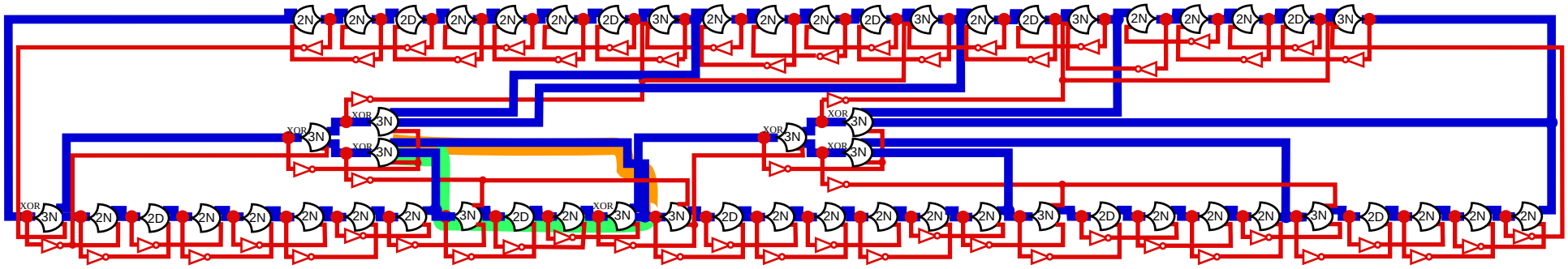
The new ring is slightly wavefront limited delivering 20 wavefront every 144 tics or 13.88 wavefronts per hundred tics. This is greater than the current limit of 13.56 wavefronts per 100 tics and does not further limit the throughput of the LFSR structure.

Step 9

Specification graft model



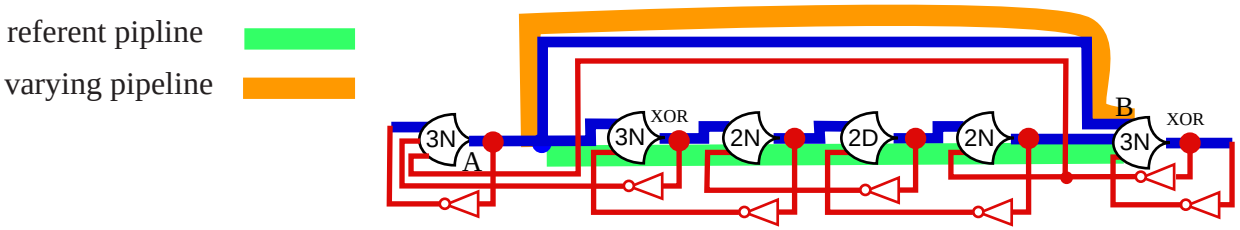
2NCL graft model



referent pipline

varying pipeline

Step 9
Isolation model



cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
1	7	21	23	3/23	13.04	bubble
2	7	21	26	3/26	11.54	bubble
3	7	21	29	3/29	10.34	bubble
4	7	21	32	3/32	9.38	bubble

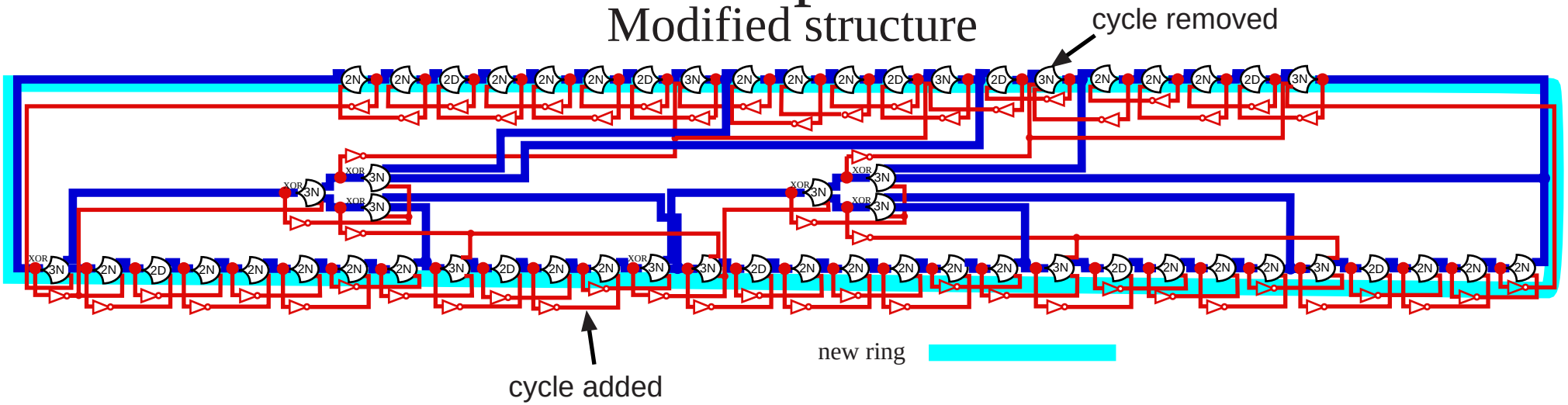
The analysis indicates that 13.04 wavefronts per 100 tics is the best that can be achieved by modifying the variable pipeline of the isolation model. It will be noticed that the isolation model is the isolation model of step 2 upside down and that a throughput of 13.64 wavefronts per 100 tics can be achieved if a buffer cycle is added to the referent pipeline of the isolation model. In this circumstance the referent pipeline is a part of the step 3 graft and it will be remembered that there was some flexibility about where to remove the cycles of that graft. If both cycles are removed from the upper part of the graft then there will be an extra cycle in the lower part of the graft which comprises the referent pipeline of the isolation model and provides the extra cycle needed in the referent pipeline for the desired throughput.

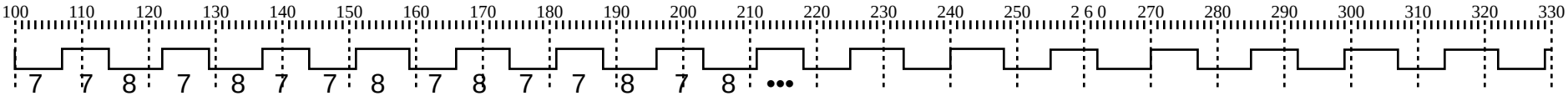
One cycle is removed from the upper pipeline segment of graft 3 and one cycle is added to the lower pipeline segment of graft 3.

The throughput is greater than the already established limit for the LFSR structure and does not further limit its throughput which remains 13.56 wavefronts per 100 tics.

Step 9

Modified structure





The new pipeline structure does not quite deliver the expected throughput. Jitter among the four inputs of the leftmost middle XOR gates is now affecting the throughput. The new structure delivers a repeating cycle period pattern of 7,7,8,7,8,... five wavefronts every 37 tics or 13.51 wavefronts per 100 tics. This simulation result is accepted as the throughput for the LFSR structure.

New ring performance

		Population period	Rejoin period	Limiting behavior mode
cycles	38			
wavefronts	16	112	114	wavefront
bubbles	22	154	152	

The new ring is slightly wavefront limited delivering 16 wavefronts every 114 tics or 14.03 wavefronts per hundred tics. This is greater than the current limit of 13.51 wavefronts per 100 tics and does not further limit the throughput of the LFSR structure.

Summary

Because there is no slowest cycle, and hence no throughput plateau, the resulting structure is uniquely optimal. Every graft except graft 3 was tuned to the only configuration that delivered adequate throughput. The flexibility in graft 3 was used up in optimizing graft 9.

If a cycle is added anywhere in the structure it will decrease the throughput.

If a cycle is removed anywhere in the structure it will decrease the throughput.

Using purely static relationships derived from the structure itself and the delay components of the structure a complex structure of pipelines was constructed with demonstrably optimal efficiency delivering the maximal throughput performance with minimal resources.

Using cycles with a 7 tic period allowing a maximum throughput of 1 wavefront every 7 tics or 5 wavefronts every 35 tics, the construction began with a ring delivering a throughput of 5 wavefronts every 36 tics and culminated in a complex structure of pipelines with a throughput of 5 wavefronts every 37 tics.

LFSR with One Slow Cycle

One slow cycle with a period of 11 tics limits the throughput of the structure to one wavefront every 11 tics or 9.09 wavefronts per 100 tics.

This slow cycle forms a delay limited plateau of behavior for the initial ring. The ring can be configured at the edge of the plateau with the fewest cycles which is the bubble limited edge.

This slow cycle will not be present in the isolation models but it can be considered as an existing upper throughput limit. Each grafted pipeline need only be configured to sustain a throughput equal to or greater than 9.09 wavefronts per 100 tics.

The step 1 initial ring can be 7 cycles instead of 9 cycles.
The step 2 graft can be 4 cycles instead of 6 cycles.
The step 3 graft can be 8 cycles instead of 11 cycles.
The step 4 graft can be 4 cycles instead of 6 cycles.
The step 5 graft can be 4 cycles instead of 7 cycles.
The step 6 graft can be 4 cycles instead of 6 cycles.
The step 7 graft can be 5 cycles instead of 8 cycles.
The step 8 graft can be 5 cycles instead of 8 cycles.
The step 9 graft can be 4 cycles instead of 6 cycles.

The Delay Plateau

Inital subring with all cycle periods 7 tics

cycles in ring	limiting cycle period	bubbles in ring	bubble population period	bubble rejoin period	wavefronts in ring	wavefront population period	wavefront rejoin period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
14	7	10	70	56	4	28	42	4/42	9.52	Wavefront
13	7	9	63	52	4	28	39	4/39	10.26	Wavefront
12	7	8	56	48	4	28	36	4/36	11.11	Wavefront
11	7	7	49	44	4	28	33	4/33	12.12	Wavefront
10	7	6	42	40	4	28	30	4/30	13.33	Wavefront
9	7	5	35	36	4	28	27	5/36	13.88	Bubble
8	7	4	28	32	4	28	24	4/32	12.5	Bubble
7	7	3	21	28	4	28	21	3/28	10.7	Bubble
6	7	2	14	24	4	28	18	2/24	8.33	Bubble
5	7	1	7	20	4	28	15	1/20	5.0	Bubble

Inital subring with one slow cycle period of 11 tics

cycles in ring	limiting cycle period	bubbles in ring	bubble population period	bubble rejoin period	wavefronts in ring	wavefront population period	wavefront rejoin period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
14	11	10	100	56	4	44	46	4/47	8.51	Wavefront
13	11	9	99	52	4	44	43	1/11	9.09	Delay
12	11	8	88	48	4	44	40	1/11	9.09	Delay
11	11	7	77	44	4	44	37	1/11	9.09	Delay
10	11	6	66	40	4	44	34	1/11	9.09	Delay
9	11	5	55	36	4	44	31	1/11	9.09	Delay
8	11	4	44	32	4	44	28	1/11	9.09	Delay
7	11	3	33	28	4	44	25	1/11	9.09	Delay
6	11	2	22	24	4	44	22	2/24	8.33	Bubble
5	11	1	11	20	4	44	19	1/20	5.0	Bubble

New Graft Structure for each Step

Step 2

cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	15	1/15	6.66	renewal
4	7	14	19	2/19	10.52	renewal
5	7	21	23	3/23	13.04	renewal
6	7	21	22	3/22	13.64	renewal
7	7	21	25	3/25	12.00	renewal
8	7	21	28	3/28	10.71	renewal
9	7	21	31	3/31	9.68	renewal
10	7	21	34	3/34	8.82	renewal

Step 3

cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
7	7	21	34	3/34	8.82	renewal
8	7	28	38	4/38	10.53	renewal
9	7	35	42	5/42	11.90	renewal
10	7	42	46	6/46	13.04	renewal
11	7	49	50	7/50	14.00	renewal
12	7	42	44	6/44	13.63	renewal
13	7	42	47	6/47	12.76	renewal

Step 4

cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	15	1/15	6.66	renewal
4	7	14	19	2/19	10.52	renewal
5	7	21	23	3/23	13.04	renewal
6	7	21	22	3/22	13.64	renewal
7	7	21	25	3/25	12.00	renewal
8	7	21	28	3/28	10.71	renewal
9	7	21	31	3/31	9.68	renewal
10	7	21	34	3/34	8.82	renewal

Step 5

cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	10	18	1/18	4.16	renewal
4	7	20	22	2/22	9.09	renewal
5	7	30	26	3/26	11.54	renewal
6	7	40	30	4/30	13.33	renewal
7	7	40	29	4/29	13.79	renewal
8	7	40	32	4/32	12.50	renewal
9	7	40	35	4/35	11.43	renewal

Step 6

cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	15	1/15	6.66	renewal
4	7	14	19	2/19	10.52	renewal
5	7	21	23	3/23	13.04	renewal
6	7	21	22	3/22	13.64	renewal
7	7	21	25	3/25	12.00	renewal
8	7	21	28	3/28	10.71	renewal
9	7	21	31	3/31	9.68	renewal
10	7	21	34	3/34	8.82	renewal

Step 7

cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	Limiting behavior Mode
3	7	7	21	1/21	4.76	renewal
4	7	14	25	2/25	8.00	renewal
5	7	21	29	3/29	10.34	renewal
6	7	28	33	4/33	12.12	renewal
7	7	35	37	5/37	13.51	renewal
8	7	35	36	5/36	13.89	renewal
9	7	35	39	5/39	12.82	renewal
10	7	35	42	5/42	11.90	renewal

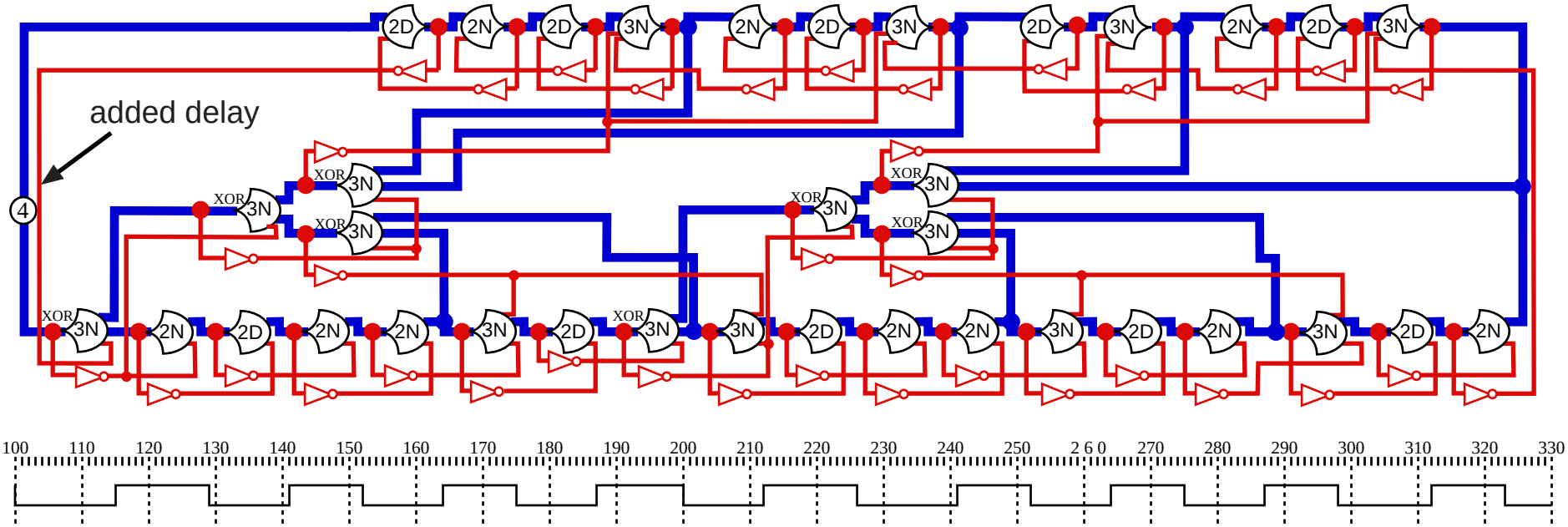
Step 8

cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	21	1/21	4.76	renewal
4	7	14	25	2/25	8.00	renewal
5	7	21	29	3/29	10.34	renewal
6	7	28	33	4/33	12.12	renewal
7	7	35	37	5/37	13.51	renewal
8	7	35	36	5/36	13.89	renewal
9	7	35	39	5/39	12.82	renewal
10	7	35	42	5/42	11.90	renewal

Step 9

cycles in upper pipeline	limiting cycle period	relevant population period	relevant renewal period	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
3	7	7	15	1/15	6.66	renewal
4	7	14	19	2/19	10.52	renewal
5	7	21	23	3/23	13.04	renewal
6	7	21	22	3/22	13.64	renewal
7	7	21	25	3/25	12.00	renewal
8	7	21	28	3/28	10.71	renewal
9	7	21	31	3/31	9.68	renewal
10	7	21	34	3/34	8.82	renewal

New LFSR Structure



Simulation reveals a repeating pattern of wavefront periods;
15,14,12,11,12,11,12,13,12,14,15,11,12,11,12,11,14,11,...

This is a throughput of 18 wavefronts every 223 tics or 8.07 wavefronts per 100 tics; somewhat less than the expected throughput of 1 wavefront per 11 tics or 9.09 wavefronts per 100 tics.

The slowest cycle is much slower than all the other cycles. It will cast its shadow through the structure making all other cycles wait and essentially buffering any jitter in other parts of the structure.

It should be possible to achieve a throughput of exactly 1 wavefront every 11 tics

Check New Ring for each Step

While the isolation structures were considered for the new delay configuration the new ring associated with each new graft was not considered.

step	cycles	wave fronts	wavefront population period	wavefront rejoin period	bubbles	bubble population period	bubble rejoin period	limiting behavior Mode	throughput waves/ 100 tics
1	7	4	44	22	3	33	28	delay	9.09
2	10	6	66	30	4	44	40	delay	9.09
3	17	10	110	51	7	77	68	delay	9.09
4	20	12	132	60	8	88	80	delay	9.09
5	23	14	154	69	9	99	92	delay	9.09
6	26	16	176	78	10	110	104	delay	9.09
7	28	18	198	87	10	110	112	bubble	8.92
8	30	20	220	96	10	110	120	bubble	8.33
9	25	16	176	81	9	99	100	bubble	9.00

The graft rings of steps 7, 8 and 9 are bubble limited and do not support the desired throughput. There are too few cycles in the ring and buffer cycles must be added to increase the bubble population.

Adjusting the Ring Througputs

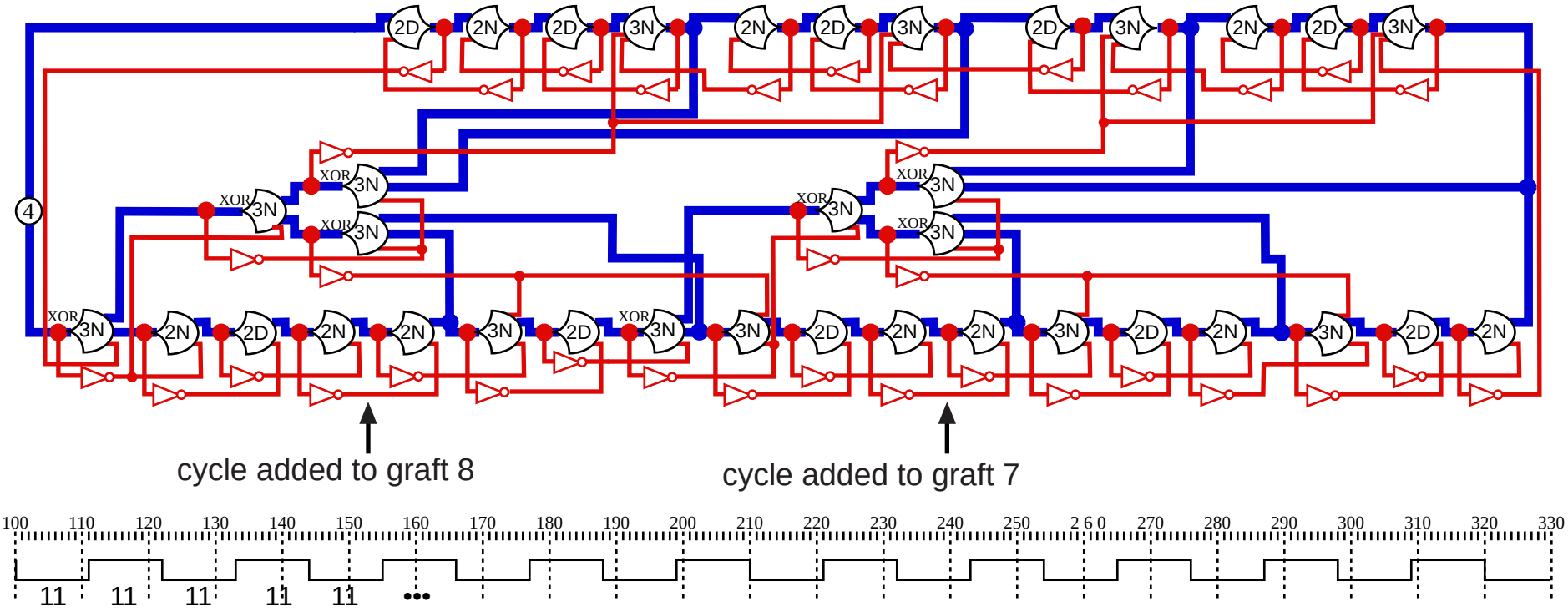
Adding a buffer cycle to the step 7 graft and hence to its ring also adds a cycle to the rings of step 8 and step 9.

step	cycles	wave fronts	wavefront population period	wavefront rejoin period	bubbles	bubble population period	bubble rejoin period	limiting behavior Mode	throughput waves/ 100 tics
7	29	18	198	87	11	121	116	delay	9.09
8	31	20	220	96	11	121	124	bubble	8.87
9	26	16	176	81	10	110	104	delay	9.09

The ring of step 8 is still bubble limited. Adding a buffer cycle to the step 8 graft and hence to its ring does not add a cycle to any other ring in the structure.

step	cycles	wave fronts	wavefront population period	wavefront rejoin period	bubbles	bubble population period	bubble rejoin period	limiting behavior Mode	throughput waves/ 100 tics
7	29	18	198	87	11	121	116	delay	9.09
8	32	20	220	96	12	132	128	delay	9.09
9	26	16	176	81	10	110	104	delay	9.09

The Final Delay Limited LFSR Structure



The throughput of the delay limited structure is now one wavefront every 11 tics or 9.09 wavefronts per 100 tics.

Summary

Both examples were synthesized to an optimal configuration of maximal throughput with minimal resources entirely in terms of static relationships derived from the structure itself and the static delay components of the structure.

While a dynamic simulation was used to verify and guide the synthesis it was not used to search a large possibility space. The possibility space was reduced almost to unity in terms of the static analysis.

The easily automatable methodology consists of constructing behavior profile tables of static relationships among static parameters and searching the table for a maximum value.

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