4x4 Butler Matrix System B Results
Compiled by Amanda Kristoff
February 9, 2009

MODEL SCHEMATICS ......................................................................................................................... 3
ISOLATION RESULTS .......................................................................................................................... 5
RETURN LOSS RESULTS ....................................................................................................................... 7
TRANSMISSION RESULTS .................................................................................................................... 9

PHASE RESULTS ...................................................................................................................................... 18

Figure 1: Ideal 4x4 Butler Matrix System B Model .............................................................................. 3
Figure 2: 4x4 Butler Matrix System B N-port Data Model ................................................................. 3
Figure 3: 4x4 Butler Matrix System B N-port Data Model with SMA Connector Model ............... 3
Figure 4: Ideal System Isolation ........................................................................................................... 5
Figure 5: N-port System Isolation ....................................................................................................... 5
Figure 6: Ideal system with N-port 90° coupler Isolation ................................................................. 5
Figure 7: Ideal system with N-port 180° coupler Isolation ................................................................. 5
Figure 8: N-port System Isolation with SMA Connector Model ...................................................... 5
Figure 9: Ideal System Return Loss .................................................................................................... 7
Figure 10: N-port System Return Loss .............................................................................................. 7
Figure 11: Ideal system with N-port 90° coupler Return Loss ......................................................... 7
Figure 12: Ideal system with N-port 180° coupler Return Loss ....................................................... 7
Figure 13: N-port System Return Loss with SMA Connector Model ............................................... 7
Figure 14: Ideal System Transmission ............................................................................................... 9
Figure 15: N-port System Transmission ............................................................................................. 9
Figure 16: Ideal system with N-port 90° coupler Transmission ....................................................... 9
Figure 17: Ideal system with N-port 180° coupler Transmission ..................................................... 9
Figure 18: N-port System Transmission with SMA Connector Model ........................................... 9
Figure 19: Ideal System Transmission Error output port 1 ........................................................... 11
Figure 20: N-port System Transmission Error output port 1 ........................................................ 11
Figure 21: Ideal system with N-port 90° coupler Transmission Error output port 1 ..................... 11
Figure 22: Ideal system with N-port 180° coupler Transmission Error output port 1 .................... 11
Figure 23: N-port System Transmission Error output port 1 with SMA Connector Model ............ 11
Figure 24: Ideal System Transmission Error output port 2 ........................................................... 13
Figure 25: N-port System Transmission Error output port 2 ........................................................ 13
Figure 26: Ideal system with N-port 90° coupler Transmission Error output port 2 .................... 13
Figure 27: Ideal system with N-port 180° coupler Transmission Error output port 2 .................... 13
Figure 28: N-port System Transmission Error output port 2 with SMA Connector Model .......... 13
Figure 29: Ideal System Transmission Error output port 3 ........................................................... 15
Figure 30: N-port System Transmission Error output port 3 ........................................................ 15
Figure 31: Ideal system with N-port 90° coupler Transmission Error output port 3 ..................... 15
Figure 32: Ideal system with N-port 180° coupler Transmission Error output port 3 .................... 15
Figure 33: N-port System Transmission Error output port 3 with SMA Connector Model .......... 15
Figure 34: Ideal System Transmission Error output port 4 ........................................................... 17
Figure 35: N-port System Transmission Error output port 4 ........................................................ 17
Figure 36: Ideal system with N-port 90° coupler Transmission Error output port 4 ..................... 17
Figure 37: Ideal system with N-port 180° coupler Transmission Error output port 4 .................... 17
Figure 38: N-port System Transmission Error output port 4 with SMA Connector Model .......... 17
Figure 39: Ideal System Phase Error output port 1 ................................................................. 19
Figure 40: N-port System Phase Error output port 1 ................................................................. 19
Figure 41: Ideal system with N-port 90° coupler Phase Error output port 1 ............................... 19
Figure 42: Ideal system with N-port 180° coupler Phase Error output port 1 ............................... 19
Figure 43: N-port System Phase Error output port 1 with SMA Connector Model .................. 19
Figure 44: Ideal System Phase Error output port 2 ................................................................. 21
Figure 45: N-port System Phase Error output port 2 ................................................................. 21
Figure 46: Ideal system with N-port 90° coupler Phase Error output port 2 ............................... 21
Figure 47: Ideal system with N-port 180° coupler Phase Error output port 2 ............................... 21
Figure 48: N-port System Phase Error output port 2 with SMA Connector Model .................. 21
Figure 49: Ideal System Phase Error output port 3 ................................................................. 23
Figure 50: N-port System Phase Error output port 3 ................................................................. 23
Figure 51: Ideal system with N-port 90° coupler Phase Error output port 3 ............................... 23
Figure 52: Ideal system with N-port 180° coupler Phase Error output port 3 ............................... 23
Figure 53: N-port System Phase Error output port 3 with SMA Connector Model .................. 23
Figure 54: Ideal System Phase Error output port 4 ................................................................. 25
Figure 55: N-port System Phase Error output port 4 ................................................................. 25
Figure 56: Ideal system with N-port 90° coupler Phase Error output port 4 ............................... 25
Figure 57: Ideal system with N-port 180° coupler Phase Error output port 4 ............................... 25
Figure 58: N-port System Phase Error output port 4 with SMA Connector Model .................. 25
Figure 59: Ideal System Phase Progression input port 1 .......................................................... 27
Figure 60: N-port System Phase Progression input port 1 .......................................................... 27
Figure 61: Ideal system with N-port 90° coupler Phase Progression input port 1 ....................... 27
Figure 62: Ideal system with N-port 180° coupler Phase Progression input port 1 ....................... 27
Figure 63: N-port System Phase Progression input port 1 with SMA Connector Model ........... 27
Figure 64: Ideal System Phase Progression input port 2 .......................................................... 29
Figure 65: N-port System Phase Progression input port 2.......................... 29
Figure 66: Ideal system with N-port 90° coupler Phase Progression input port 2........... 29
Figure 67: Ideal system with N-port 180° coupler Phase Progression input port 2........... 29
Figure 68: N-port System Phase Progression input port 2 with SMA Connector Model..... 29
Figure 69: Ideal System Phase Progression input port 3 ........................................ 31
Figure 70: N-port System Phase Progression input port 3.......................... 31
Figure 71: Ideal system with N-port 90° coupler Phase Progression input port 3............. 31
Figure 72: Ideal system with N-port 180° coupler Phase Progression input port 3............. 31
Figure 73: N-port System Phase Progression input port 3 with SMA Connector Model..... 31
Figure 74: Ideal System Phase Progression input port 4 ........................................ 33
Figure 75: N-port System Phase Progression input port 4........................................ 33
Figure 76: Ideal system with N-port 90° coupler Phase Progression input port 4............. 33
Figure 77: Ideal system with N-port 180° coupler Phase Progression input port 4............. 33
Figure 78: N-port System Phase Progression input port 4 with SMA Connector Model..... 33

Model Schematics

Figure 1: Ideal 4x4 Butler Matrix System B Model

Figure 2: 4x4 Butler Matrix System B N-port Data Model

Figure 3: 4x4 Butler Matrix System B N-port Data Model with SMA Connector Model

Figure 1 shows the ideal system connections for a 4x4 Butler matrix utilizing three 180° couplers and one 90° coupler as modeled in Ansoft Designer by Amanda Kristoff. Figure 2 shows the system connections utilizing N-port data from components designed utilizing HFSS as modeled by Amanda Kristoff in Ansoft Designer. The system is assembled using the N-port data from the 90° Coupler designed by Michael Pecararo in HFSS and 180° Coupler designed by Joel...
Barry in HFSS. Additional transmission lines and bends were designed by Joel Barry to connect the components. Figure 3 shows the complete system with additional SMA connector launches. The SMA connector launch was designed by Michael Pecararo in HFSS.
In the scope of this document, ports labeled 1 through 4 in the system are considered input ports. Ports labeled 5 through 8 are considered input ports 1 through 4.
Isolation Results

**Figure 4:** Ideal System Isolation

**Figure 5:** N-port System Isolation

**Figure 6:** Ideal system with N-port 90° coupler Isolation

**Figure 7:** Ideal system with N-port 180° coupler Isolation

**Figure 8:** N-port System Isolation with SMA Connector Model
Figure 4 shows the isolation of the ideal system. This will be used as a baseline comparison for the overall performance of the N-port system. Figure 5 shows the N-port system isolation. It can be easily seen that the isolation has decreased across the X-band frequency range.

By examining Figure 6 and Figure 7, one will note that the majority of the isolation loss is due to the 180° coupler. The 90° coupler only affects S33 and S44 and this impact is not compounded by additional non-ideal components in the system. The deterioration of isolation is greatest at the 11GHz, where initially in the ideal system this was much lower. The 180° coupler affects S11 and S22. Because the isolation at S11 and S22 are initially greater than S33 and S44 and remain greater even with the non-ideal 90° coupler, it can be concluded that 180° coupler will be the source of the most loss of isolation. The remaining decreases in isolation can be attributed to the additional bends and transmission lines necessary to connect the components. This has the most affect at the outer range of 10 to 12 GHz while 11GHz remains somewhat stable as compared to the ideal with N-port data from either the 90° coupler or 180° coupler. The bends also have no affect on S33 and S44. Figure 8 shows that SMA connector model has resulted in a small loss of isolation at 10 GHz but has slightly improved isolation at higher frequencies.
Return Loss Results

Figure 9: Ideal System Return Loss

Figure 10: N-port System Return Loss

Figure 11: Ideal system with N-port 90° coupler Return Loss

Figure 12: Ideal system with N-port 180° coupler Return Loss

Figure 13: N-port System Return Loss with SMA Connector Model
Figure 9 shows the return loss of the ideal system. This will be used as a baseline comparison for the overall performance of the N-port system. This initial simulation shows that the majority if the return loss occurs at S43 with the second worst being S21. The remaining return loss results are relatively consistent. Figure 10 shows the N-port system return loss. It can be seen that the return loss has increased over the entire 10 to 12 GHz frequency range and has drastically decreased at 11 GHz.

Figure 11 and Figure 12 show the affect of the individual components, the 90° coupler and 180° coupler respectively, by inserting the N-port component into the ideal system. The 90° coupler has improved the return loss for S43 at 10 GHz but has caused increased return loss at higher frequencies. The other ports are not affected by the non-ideal coupler. The 180° coupler affects all ports, due to the increased use of the coupler in the system. S43 has greatly increased return loss at all frequencies. The remaining ports have increased return loss mainly at 11 GHz.

Figure 10 shows the affects of combining the two non-ideal components with additional transmission lines. Since the 90° coupler only affects S43, this is the only signal where improvements can be seen in the return loss as compared to the effects of the 180° coupler. Additional return loss can be seen in S21 and some return loss in S43 can be attributed to the additional transmission lines. Figure 13 shows that SMA connector model has decreased return loss at 10 GHz, increased at 11 GHz and remained the same at 12 GHz. Overall, the connector model does not have a significant impact on the performance of the system.
Transmission Results

**Overall System**

Figure 14: Ideal System Transmission

Figure 15: N-port System Transmission

Figure 16: Ideal system with N-port 90° coupler Transmission

Figure 17: Ideal system with N-port 180° coupler Transmission

Figure 18: N-port System Transmission with SMA Connector Model
Figure 14 shows the overall transmission of the system across all ports. This will be used as a baseline comparison for the overall performance of the N-port system. It can be seen that the transmission is -6dB at 11 GHz and fluctuates up to +0.16 and -0.23 at the edges of the frequency range. Figure 15 shows that the overall transmission of the system has dropped to -6.5dB with a fluctuation up to +0.17 and -0.22 at the edges of the frequency range. The transmission error for each port will be looked at in a later section.

Figure 16 and Figure 17 show the affect of the individual components, the 90° coupler and 180° coupler respectively, by inserting the N-port component into the ideal system. The 180° coupler has caused the majority of the decreased transmission except for transmission to output ports 3 and 4. The decreased transmission is from input ports 3 and 4 is caused by the 90° coupler. This is logical since these are the only ports connected to the 90° coupler while the remaining ports are connected to the 180° coupler. The remaining transmission loss can be attributed to the additional transmission lines and bends. Figure 18 shows that the addition of the SMA connector model has resulted in a loss of transmission across all frequencies.

**Transmission Error**

The error rate looked at takes the average of all the transmissions for all input ports and subtracts the transmission at the output port being looked at from this dependent upon which input port is being looked at. For example, when looking at the transmission error at output port 1 from input port 1, the formula used is \(((\text{db}(S_{51})+\text{db}(S_{52})+\text{db}(S_{53})+\text{db}(S_{54}))/4)-\text{db}(S_{51})\) where output port 1 is number five and input port 1 is number one.
Figure 19: Ideal System Transmission Error output port 1

Figure 20: N-port System Transmission Error output port 1

Figure 21: Ideal system with N-port 90° coupler Transmission Error output port 1

Figure 22: Ideal system with N-port 180° coupler Transmission Error output port 1

Figure 23: N-port System Transmission Error output port 1 with SMA Connector Model
Figure 19 shows the transmission error of the system at output port 1. This will be used as a baseline comparison for the overall performance of the N-port system. The error is zero at 11GHz and fluctuates +0.11 and – 0.19 at the edges of the frequency range. Figure 20 shows that the error rate has increased for all input ports across the whole frequency range. The fluctuation have increased up to +0.33 and -0.20 across the frequency range.

Figure 21 and Figure 22 show the affect of the individual components, the 90° coupler and 180° coupler respectively, by inserting the N-port component into the ideal system. Both components have an affect on all the input ports examined. The 90° coupler affects the fourth input port the most. This can be attributed to the system topology and the fourth input port being connected to the 90° coupler. Even though the 180° coupler has a negative error for input port four, most likely due to the system topology, the system error is still positive due to the topology the 90° coupler is the most influential. This could also be a reason why the third input port is not as negative as it was in the ideal system with the non-ideal 180° coupler in the final system. It seems that the affect of both coupler balance each other a bit for the first and second input ports causing a decrease in transmission error. Remaining transmission error can be attributed to the additional transmission lines and bends. Figure 23 shows that the SMA connector model does not have a significant impact on the transmission error of the system.
Figure 24: Ideal System Transmission Error output port 2

Figure 25: N-port System Transmission Error output port 2

Figure 26: Ideal system with N-port 90° coupler Transmission Error output port 2

Figure 27: Ideal system with N-port 180° coupler Transmission Error output port 2

Figure 28: N-port System Transmission Error output port 2 with SMA Connector Model
Figure 24, Figure 25, Figure 26, Figure 27 and Figure 28 show similar results as seen in output ports 1. Similar conclusions can be drawn as previously seen.
Output Port 3

Figure 29: Ideal System Transmission Error output port 3

Figure 30: N-port System Transmission Error output port 3

Figure 31: Ideal system with N-port 90° coupler Transmission Error output port 3

Figure 32: Ideal system with N-port 180° coupler Transmission Error output port 3

Figure 33: N-port System Transmission Error output port 3 with SMA Connector Model
Figure 29, Figure 30, Figure 31, Figure 32 and Figure 33 show similar results as seen in output ports 1 and 2. Similar conclusions can be drawn as previously seen.
Output Port 4

Figure 34: Ideal System Transmission Error output port 4

Figure 35: N-port System Transmission Error output port 4

Figure 36: Ideal system with N-port 90° coupler Transmission Error output port 4

Figure 37: Ideal system with N-port 180° coupler Transmission Error output port 4

Figure 38: N-port System Transmission Error output port 4 with SMA Connector Model
Figure 34, Figure 35, Figure 36, Figure 37 and Figure 38 show similar results as seen in output ports 1, 2, and 3. Similar conclusions can be drawn as previously seen.

**Phase Results**

**Phase Error**

The error rate looked at first uses input port 1 as a reference line and takes the difference between the input port being looked at and input port 1 and also subtracts the expected phase progression. Then the average is taken of these three differences and difference between the reference line and the input port being looked at is subtracted from this average to get the phase error. For example, when looking at the phase error of input port 1 from output port 1 to 2 the formula would be \(((\text{cang}\_\text{deg}(S51)-\text{cang}\_\text{deg}(S61))+(\text{cang}\_\text{deg}(S51)-\text{cang}\_\text{deg}(S71))+(\text{cang}\_\text{deg}(S51)-\text{cang}\_\text{deg}(S81)))/3)-(\text{cang}\_\text{deg}(S51)-\text{cang}\_\text{deg}(S51))\) where 1 is input port 1, 5 is output port 1, 6 is output port 2, etc.
Output Port 1

Figure 39: Ideal System Phase Error output port 1

Figure 40: N-port System Phase Error output port 1

Figure 41: Ideal system with N-port 90° coupler
Phase Error output port 1

Figure 42: Ideal system with N-port 180° coupler
Phase Error output port 1

Figure 43: N-port System Phase Error output port 1 with SMA Connector Model
Figure 39 shows the phase error of the system at output port 1. This will be used as a baseline comparison for the overall performance of the N-port system. The error is zero at 11 GHz and fluctuates up to -0.51° at 10 GHz and +0.54° at 12 GHz. Figure 40 has shown that error between output ports 1 and 4 has become more negative and the error between output port 1 and the remaining two ports has increased. The error is the least at 10 GHz and is fairly consistent at the increased frequencies until 12 GHz where it increases again. The error is up to +0.36° and -0.60° at 12 GHz.

Figure 41 and Figure 42 show that the 90° coupler has little influence on the phase error. The majority of the phase error can be attributed to the 180° coupler. The remaining increases in phase error are due to the additional transmission lines. Figure 43 shows that the SMA connector model does not have a significant impact on the phase error.
Figure 44: Ideal System Phase Error output port 2

Figure 45: N-port System Phase Error output port 2

Figure 46: Ideal system with N-port 90° coupler
Phase Error output port 2

Figure 47: Ideal system with N-port 180° coupler
Phase Error output port 2

Figure 48: N-port System Phase Error output port 2 with SMA Connector Model
Figure 44, Figure 45, Figure 46, Figure 47, and Figure 48 show similar results as seen in output port 1. Similar conclusions can be drawn as previously seen.
Figure 49: Ideal System Phase Error output port 3

Figure 50: N-port System Phase Error output port 3

Figure 51: Ideal system with N-port 90° coupler
Phase Error output port 3

Figure 52: Ideal system with N-port 180° coupler
Phase Error output port 3

Figure 53: N-port System Phase Error output port 3 with SMA Connector Model
Figure 49, Figure 50, Figure 51, Figure 52, and Figure 53 show similar results as seen in output ports 1 and 2. The 90° coupler has a small increase in its affect on the phase error. Similar conclusions can be drawn as previously seen.
Output Port 4

Figure 54: Ideal System Phase Error output port 4

Figure 55: N-port System Phase Error output port 4

Figure 56: Ideal system with N-port 90° coupler Phase Error output port 4

Figure 57: Ideal system with N-port 180° coupler Phase Error output port 4

Figure 58: N-port System Phase Error output port 4 with SMA Connector Model
Figure 54, Figure 55, Figure 56, Figure 57, and Figure 58 show similar results as seen in output ports 1, 2 and 3. The 90° coupler has a small increase in its affect on the phase error. Similar conclusions can be drawn as previously seen.

**Phase Progression**

The phase progression uses output port 1 as a reference line and takes the difference between the output port being looked at and output port 1 for each input port. For example, when looking at the phase progression of input port 1 from output port 1 to 2 the formula would be cang_deg(S15)-cang_deg(S16) where 1 is the input port, 5 is output port 1 and 6 is output port 2.
Input Port 1

Figure 59: Ideal System Phase Progression input port 1

Figure 60: N-port System Phase Progression input port 1

Figure 61: Ideal system with N-port 90° coupler Phase Progression input port 1

Figure 62: Ideal system with N-port 180° coupler Phase Progression input port 1

Figure 63: N-port System Phase Progression input port 1 with SMA Connector Model
Figure 59 shows the phase progression of the system for input port 1. This will be used as a baseline comparison for the overall performance of the N-port system. Based on the specifications, the phase progression for this port should be 0°. This is seen at 11GHz but there is a progression of up to -0.76° at 10 GHz and +0.80° at 12 GHz. Figure 60 shows that the progression is not exactly zero for this output port. The exact discrepancies were previously looked at under the Phase Error heading.

Figure 61 and Figure 62 show, similarly to as seen in the Phase Error section, that the 90° coupler has little effect on the phase error and most of it can be attributed to the 180° coupler. Figure 63 shows that the SMA connector model does not have a significant impact on the phase progression.
Figure 64: Ideal System Phase Progression input port 2

Figure 65: N-port System Phase Progression input port 2

Figure 66: Ideal system with N-port 90° coupler Phase Progression input port 2

Figure 67: Ideal system with N-port 180° coupler Phase Progression input port 2

Figure 68: N-port System Phase Progression input port 2 with SMA Connector Model
Figure 64, Figure 65, Figure 66, Figure 67, and Figure 68 show similar results as seen in output port 1. Similar conclusions can be drawn as previously seen. Based on the specifications, the phase progression for this port should be 180°. It can be seen then that the outputs of two ports are 180° degrees different than the first output port and that one output is the same as the first output port. This is the expected result.
Input Port 3

Figure 69: Ideal System Phase Progression input port 3

Figure 70: N-port System Phase Progression input port 3

Figure 71: Ideal system with N-port 90° coupler Phase Progression input port 3

Figure 72: Ideal system with N-port 180° coupler Phase Progression input port 3

Figure 73: N-port System Phase Progression input port 3 with SMA Connector Model
Figure 69, Figure 70, Figure 71, Figure 72, and Figure 73 show similar results as seen in output port 1. Similar conclusions can be drawn as previously seen. Based on the specifications, the phase progression for this port should be -90°. It can be seen then that the outputs of the ports progress by -90° as expected.
Input Port 4

Figure 74: Ideal System Phase Progression input port 4

Figure 75: N-port System Phase Progression input port 4

Figure 76: Ideal system with N-port 90° coupler Phase Progression input port 4

Figure 77: Ideal system with N-port 180° coupler Phase Progression input port 4

Figure 78: N-port System Phase Progression input port 4 with SMA Connector Model
Figure 74, Figure 75, Figure 76, Figure 77, and Figure 78 show similar results as seen in output port 1. Similar conclusions can be drawn as previously seen. Based on the specifications, the phase progression for this port should be 90°. It can be seen then that the outputs of the ports progress by 90° as expected.