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Indoor Free-space Quantum Key Distribution In Daylight

Appendix

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30 minute experiment

QKD system with 41.67 MHz repetition rate and 6 ns gating window

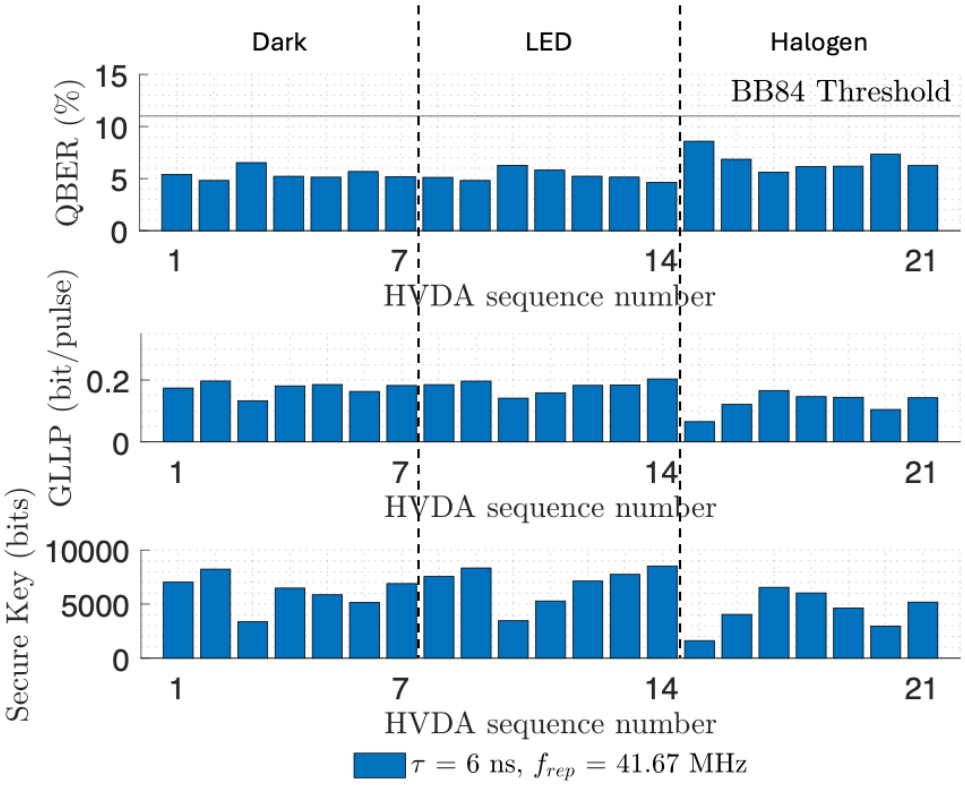
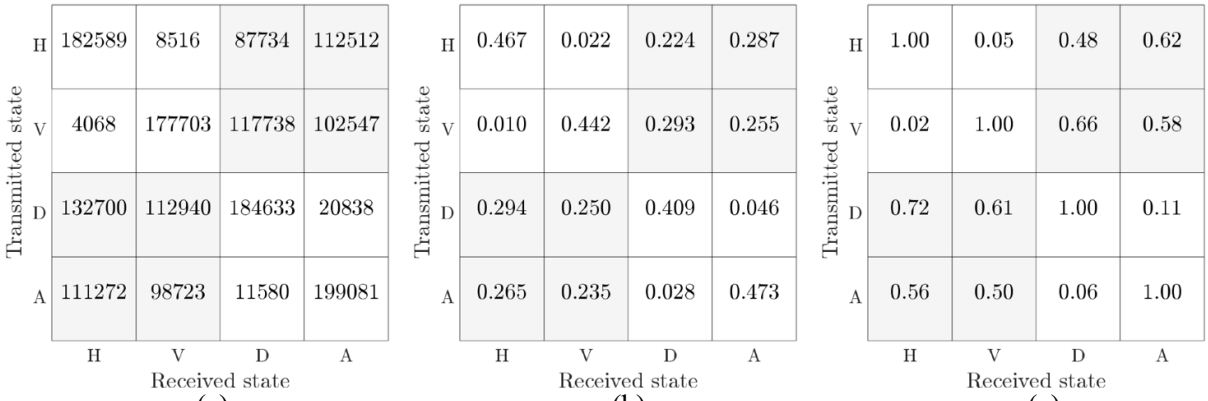


Figure 1: 30 minute experiment with a QKD system that operated at 41.67 MHz repetition rate with a 6 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp. This is equivalent to 7 HVDA sequences in darkness, 7 sequences under LED lighting, and 7 sequences under halogen lamp. Each iteration in the experiment (1 HVDA sequence) was sampled at 84 seconds. The QBER, GLLP secure key rate, and the number of secure key bits were calculated for each HVDA sequence.

Table 1: Statistical analysis for the 30 minute experiment (41.67 MHz repetition rate and 6 ns gating window)

$f_{rep} = 41.67$ MHz, $\tau = 6$ ns	Total (30 min)	Dark (10 min)	LED (10 min)	Halogen (10 min)
Total signal counts K_μ^{sig}	744,006	244,263	263,945	235,798
Total error counts K_μ^{err}	45,002	13,849	14,517	16,636
Total counts in sifted basis $K_\mu^s = K_\mu^{sig} + K_\mu^{err}$	789,008	258,112	278,462	252,434
Average QBER (%) $E_{\mu,avg}$	5.81%	5.43%	5.29%	6.71%
Average GLLP (bit/pulse) $R_{GLLP,avg}$	0.16	0.174	0.179	0.127
Average error counts $\mu_{err} = E_{\mu,avg} \times K_\mu^{sig}$	43,227	13,264	13,963	15,822
Standard deviation of error counts $\sigma_{err} = \sqrt{\mu_{err}}$	208	115	118	126
Fluctuation in QBER (%) $\frac{\sigma_{err}}{K_\mu^{sig}} \times 100$	0.028%	0.047%	0.045%	0.053%
Total secure key bits $K_{secure} = R_{GLLP,avg} \times K_\mu^{sig}$	119,041	42,502	47,246	29,946



Transmitted state \ Received state	H	V	D	A
H	182589	8516	87734	112512
V	4068	177703	117738	102547
D	132700	112940	184633	20838
A	111272	98723	11580	199081

(a)

Transmitted state \ Received state	H	V	D	A
H	0.467	0.022	0.224	0.287
V	0.010	0.442	0.293	0.255
D	0.294	0.250	0.409	0.046
A	0.265	0.235	0.028	0.473

(b)

Transmitted state \ Received state	H	V	D	A
H	1.00	0.05	0.48	0.62
V	0.02	1.00	0.66	0.58
D	0.72	0.61	1.00	0.11
A	0.56	0.50	0.06	1.00

(c)

Figure 2: Crosstalk matrices for the 30 minute experiment with a QKD system that operated at 41.67 MHz repetition rate with a 6 ns gating window. Each matrix shows (a) the distribution of received photon counts across 30 minutes, (b) the ratio of received counts in each received state (column) relative to the total received counts per transmitted state (row), and (c) the normalisation of the received states (column) relative to the maximum received counts per transmitted state (row).

Table 2: Crosstalk polarisation error calculation

30 min (41.67 MHz, 6 ns)
$(e_{D/A}\|H) = 0.62 - 0.48 = 0.14$
$(e_{D/A}\|V) = 0.66 - 0.58 = 0.08$
$(e_{H/V}\|D) = 0.72 - 0.61 = 0.11$
$(e_{H/V}\|A) = 0.56 - 0.5 = 0.06$
$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.085$
$\Delta e = 0.11 - 0.085 = 0.025$

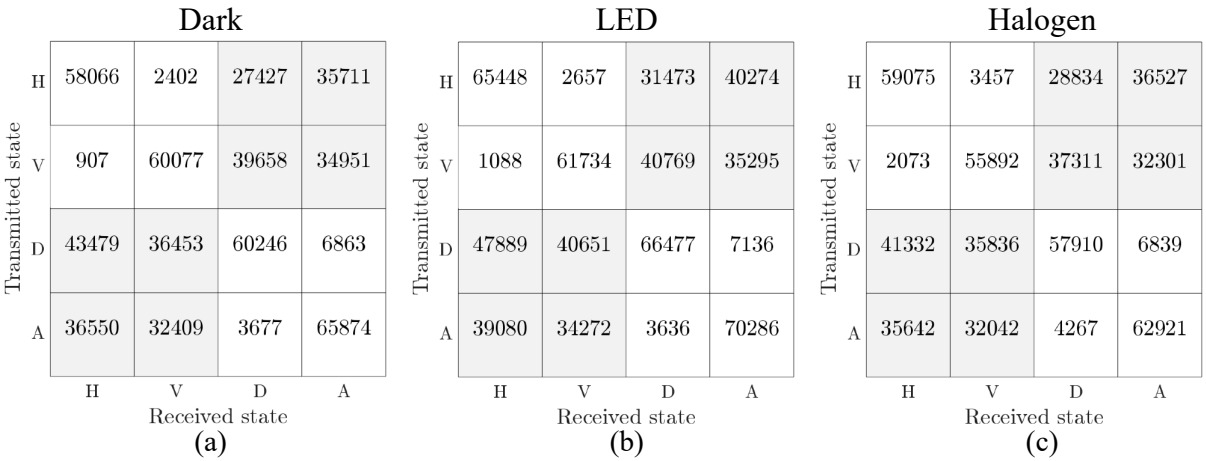


Figure 3: Crosstalk matrices that show the distribution of the received photon counts for the QKD system operated at 41.67 MHz repetition rate with a 6 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp.

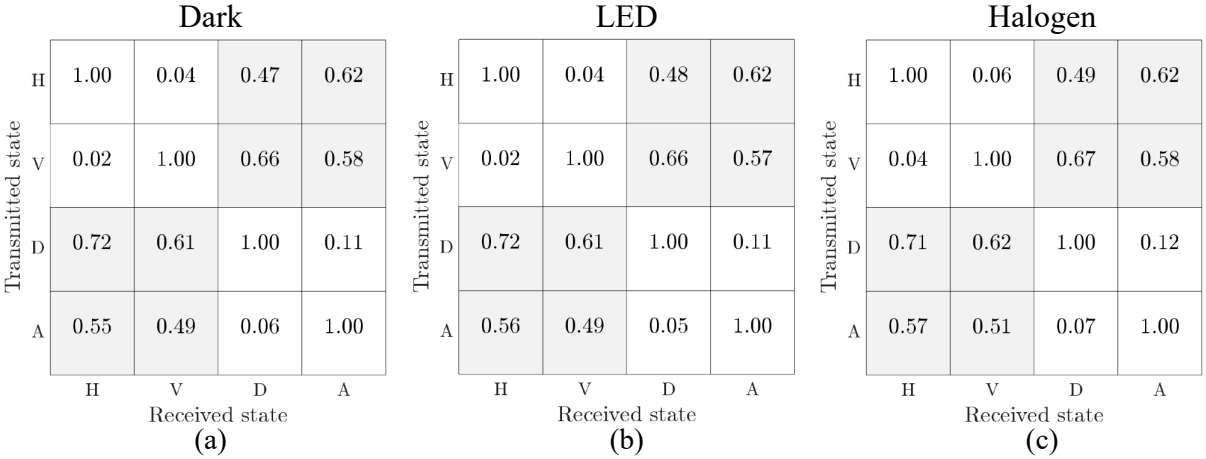


Figure 4: Normalised crosstalk matrices for the QKD system operated at 41.67 MHz repetition rate with a 6 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp. Each matrix was normalised for the received state (column) relative to the maximum received photon counts per transmitted state (row).

Table 3: Polarisation error calculation for the QKD system that ran for 30 minutes and operated at 41.67 MHz repetition rate with a 6 ns gating window. The errors were calculated for each ambient light scenario.

DARK (6 ns, 10 min)	LED (6 ns, 10 min)	HALOGEN (6 ns, 10 min)
$(e_{D/A}\|H) = 0.62 - 0.47 = 0.15$	$(e_{D/A}\|H) = 0.62 - 0.48 = 0.14$	$(e_{D/A}\|H) = 0.62 - 0.49 = 0.13$
$(e_{D/A}\|V) = 0.66 - 0.58 = 0.08$	$(e_{D/A}\|V) = 0.66 - 0.57 = 0.09$	$(e_{D/A}\|V) = 0.67 - 0.58 = 0.09$
$(e_{H/V}\|D) = 0.72 - 0.61 = 0.11$	$(e_{H/V}\|D) = 0.72 - 0.61 = 0.11$	$(e_{H/V}\|D) = 0.71 - 0.62 = 0.09$
$(e_{H/V}\|A) = 0.55 - 0.49 = 0.06$	$(e_{H/V}\|A) = 0.56 - 0.49 = 0.07$	$(e_{H/V}\|A) = 0.57 - 0.51 = 0.06$
$e_{D/A,avg} = 0.115$	$e_{D/A,avg} = 0.115$	$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.085$	$e_{H/V,avg} = 0.09$	$e_{H/V,avg} = 0.075$
$\Delta e = 0.115 - 0.085 = 0.03$	$\Delta e = 0.115 - 0.09 = 0.025$	$\Delta e = 0.11 - 0.075 = 0.035$

Table 4: Link budget analysis for 30 minute experiment (41.67 MHz repetition rate and 6 ns gating window)

Number of HVDA sequences	7		
Repetition rate (assume one photon per pulse)	41.67×10^6		
Number of transmitter channels	4		
Total signal photons	**1,166,760,000**		
	Dark	**LED**	**Halogen**
Total received counts from transmitted H	123,606	139,852	127,893
Total received counts from transmitted V	135,593	138,886	127,577
Total received counts from transmitted D	147,041	162,153	141,917
Total received counts from transmitted A	138,510	147,274	134,872
Total received counts	**544,750**	**588,165**	**532,259**
Average dark counts per detector	500	500	500
Average dark counts across 4 detectors in one HVDA sequence	2,000	2,000	2,000
Average counts from LED lighting per detector	-	0	-
Average counts from LED lighting across 4 detectors in one HVDA sequence	-	0	-
Average counts from halogen lamp per detector	-	-	300
Average counts from halogen lamp across 4 detectors in one HVDA sequence	-	-	1,200
Average counts from noise sources per transmitted state in 7 HVDA sequences	14,000	14,000	22,400
Total counts from noise sources across all 4 transmitted states	56,000	56,000	89,600
Estimated total received signal counts	**488,750**	**532,165**	**442,659**
Total loss (ratio of received signal counts / transmitted signal photons)	4.19×10^{-4}	4.56×10^{-4}	3.79×10^{-4}
Total loss in dB	33.8 dB	33.4 dB	34.2 dB
Channel loss in dB	0 dB	0 dB	0 dB
Average transmittance across all 4 receiver channels	0.0064	0.0064	0.0064
Average receiver loss in dB	21.9 dB	21.9 dB	21.9 dB
Total loss – Average receiver loss in dB	**11.9 dB**	**11.5 dB**	**12.3 dB**
Estimated mean photon number	0.065	-	-

QKD system with 41.67 MHz repetition rate and 3 ns gating window

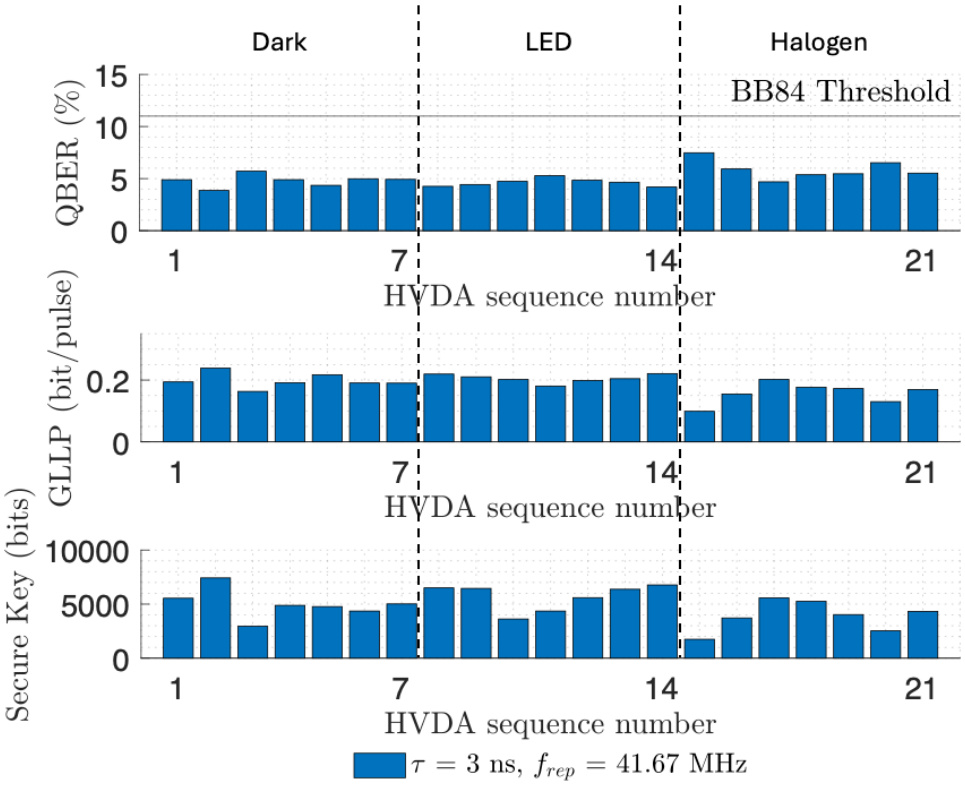


Figure 5: 30 minute experiment with a QKD system that operated at 41.67 MHz repetition rate with a 3 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp. This is equivalent to 7 HVDA sequences in darkness, 7 sequences under LED lighting, and 7 sequences under halogen lamp. Each iteration in the experiment (1 HVDA sequence) was sampled at 84 seconds. The QBER, GLLP secure key rate, and the number of secure key bits were calculated for each HVDA sequence.

Table 5: Statistical analysis for the 30 minute experiment (41.67 MHz repetition rate and 3 ns gating window)

$f_{rep} = 41.67$ MHz, $\tau = 3$ ns	Total (30 min)	Dark (10 min)	LED (10 min)	Halogen (10 min)
Total signal counts K_μ^{sig}	534,460	174,585	192,396	167,479
Total error counts K_μ^{err}	28,170	8,699	9,276	10,195
Total counts in sifted basis $K_\mu^s = K_\mu^{sig} + K_\mu^{err}$	562,630	183,284	201,672	177,674
Average QBER (%) $E_{\mu,avg}$	5.10%	4.80%	4.63%	5.85%
Average GLLP (bit/pulse) $R_{GLLP,avg}$	0.187	0.198	0.205	0.158
Average error counts $\mu_{err} = E_{\mu,avg} \times K_\mu^{sig}$	27,258	8,380	8,908	9,798
Standard deviation of error counts $\sigma_{err} = \sqrt{\mu_{err}}$	165	92	94	99
Fluctuation in QBER (%) $\frac{\sigma_{err}}{K_\mu^{sig}} \times 100$	0.031%	0.053%	0.049%	0.059%
Total secure key bits $K_{secure} = R_{GLLP,avg} \times K_\mu^{sig}$	99,944	34,568	39,441	26,462

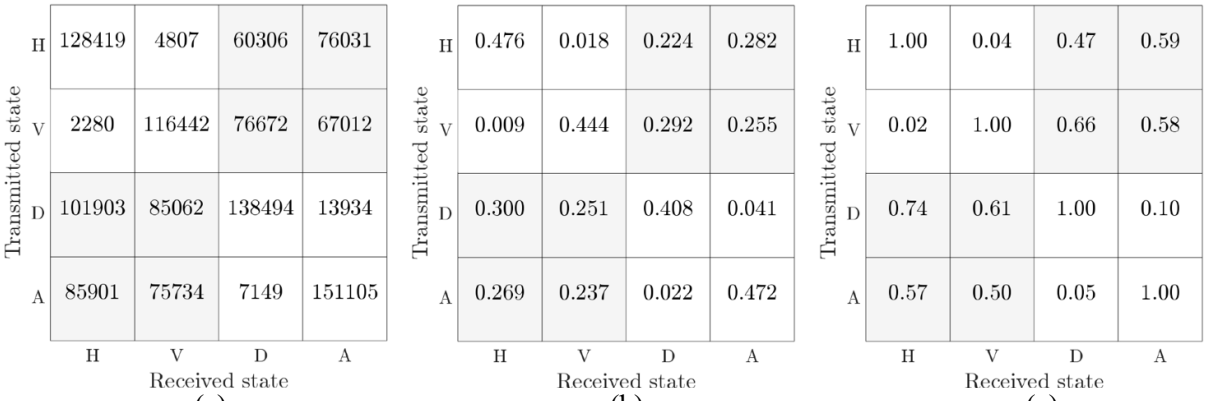


Figure 6: Crosstalk matrices for the 30 minute experiment with a QKD system that operated at 41.67 MHz repetition rate with a 3 ns gating window. Each matrix shows (a) the distribution of received photon counts across 30 minutes, (b) the ratio of received counts in each received state (column) relative to the total received counts per transmitted state (row), and (c) the normalisation of the received states (column) relative to the maximum received counts per transmitted state (row).

Table 6: Crosstalk polarisation error calculation

30 min (41.67 MHz, 3 ns)
$\left(e_{D/A}\middle\vert H\right) = 0.59 - 0.47 = 0.12$
$\left(e_{D/A}\middle\vert V\right) = 0.66 - 0.58 = 0.08$
$\left(e_{H/V}\middle\vert D\right) = 0.74 - 0.61 = 0.13$
$\left(e_{H/V}\middle\vert A\right) = 0.57 - 0.5 = 0.07$
$e_{D/A,avg} = 0.1$
$e_{H/V,avg} = 0.1$
$\Delta e = 0.1 - 0.1 = 0$

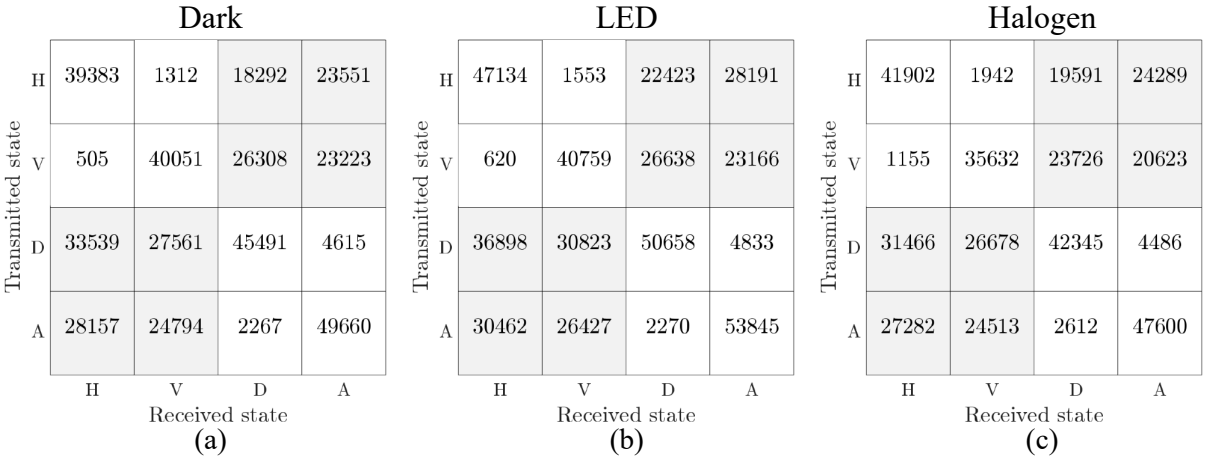


Figure 7: Crosstalk matrices that show the distribution of the received photon counts for the QKD system operated at 41.67 MHz repetition rate with a 3 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp.

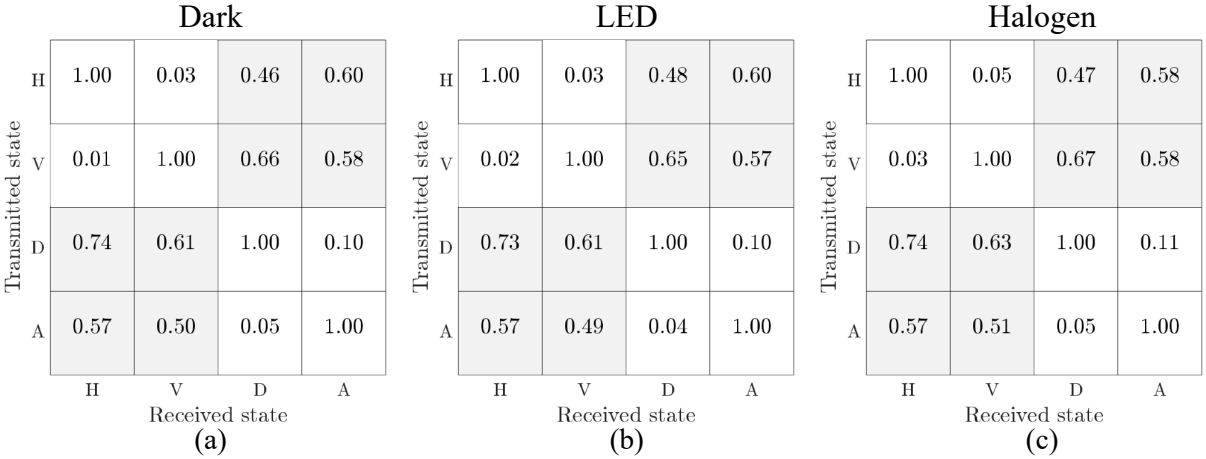


Figure 8: Normalised crosstalk matrices for the QKD system operated at 41.67 MHz repetition rate with a 3 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp. Each matrix was normalised for the received state (column) relative to the maximum received photon counts per transmitted state (row).

Table 7: Polarisation error calculation for the QKD system that ran for 30 minutes and operated at 41.67 MHz repetition rate with a 3 ns gating window. The errors were calculated for each ambient light scenario.

DARK (3 ns, 10 min)	LED (3 ns, 10 min)	HALOGEN (3 ns, 10 min)
$(e_{D/A}\|H) = 0.6 - 0.46 = 0.14$	$(e_{D/A}\|H) = 0.6 - 0.48 = 0.12$	$(e_{D/A}\|H) = 0.58 - 0.47 = 0.11$
$(e_{D/A}\|V) = 0.66 - 0.58 = 0.08$	$(e_{D/A}\|V) = 0.65 - 0.57 = 0.08$	$(e_{D/A}\|V) = 0.67 - 0.58 = 0.09$
$(e_{H/V}\|D) = 0.74 - 0.61 = 0.13$	$(e_{H/V}\|D) = 0.73 - 0.61 = 0.12$	$(e_{H/V}\|D) = 0.74 - 0.63 = 0.11$
$(e_{H/V}\|A) = 0.57 - 0.5 = 0.07$	$(e_{H/V}\|A) = 0.57 - 0.49 = 0.08$	$(e_{H/V}\|A) = 0.57 - 0.51 = 0.06$
$e_{D/A,avg} = 0.11$	$e_{D/A,avg} = 0.1$	$e_{D/A,avg} = 0.1$
$e_{H/V,avg} = 0.1$	$e_{H/V,avg} = 0.1$	$e_{H/V,avg} = 0.085$
$\Delta e = 0.11 - 0.1 = 0.01$	$\Delta e = 0.1 - 0.1 = 0$	$\Delta e = 0.1 - 0.085 = 0.015$

Table 8: Link budget analysis for the 30 minute experiment (41.67 MHz repetition rate and 3 ns gating window)

Number of HVDA sequences	7		
Repetition rate (assume one photon per pulse)	41.67×10^6		
Number of transmitter channels	4		
Total signal photons	**1,166,760,000**		
	Dark	**LED**	**Halogen**
Total received counts from transmitted H	82,538	99,301	87,724
Total received counts from transmitted V	90,087	91,183	81,136
Total received counts from transmitted D	111,206	123,212	104,975
Total received counts from transmitted A	104,878	113,004	102,007
Total received counts	**388,709**	**426,700**	**375,842**
Average dark counts per detector	500	500	500
Average dark counts across 4 detectors in one HVDA sequence	2,000	2,000	2,000
Average counts from LED lighting per detector	-	0	-
Average counts from LED lighting across 4 detectors in one HVDA sequence	-	0	-
Average counts from halogen lamp per detector	-	-	300
Average counts from halogen lamp across 4 detectors in one HVDA sequence	-	-	1,200
Average counts from noise sources per transmitted state in 7 HVDA sequences	14,000	14,000	22,400
Total counts from noise sources across all 4 transmitted states	56,000	56,000	89,600
Estimated total received signal counts	**332,709**	**370,700**	**286,242**
Total loss (ratio of received signal counts / transmitted signal photons)	2.85×10^{-4}	3.18×10^{-4}	2.45×10^{-4}
Total loss in dB	35.45 dB	35 dB	36.1 dB
Channel loss in dB	0 dB	0 dB	0 dB
Average transmittance across all 4 receiver channels	0.0064	0.0064	0.0064
Average receiver loss in dB	21.9 dB	21.9 dB	21.9 dB
Total loss – Average receiver loss in dB	**13.55 dB**	**13.1 dB**	**14.2 dB**

QKD system with 10 MHz repetition rate and 6 ns gating window

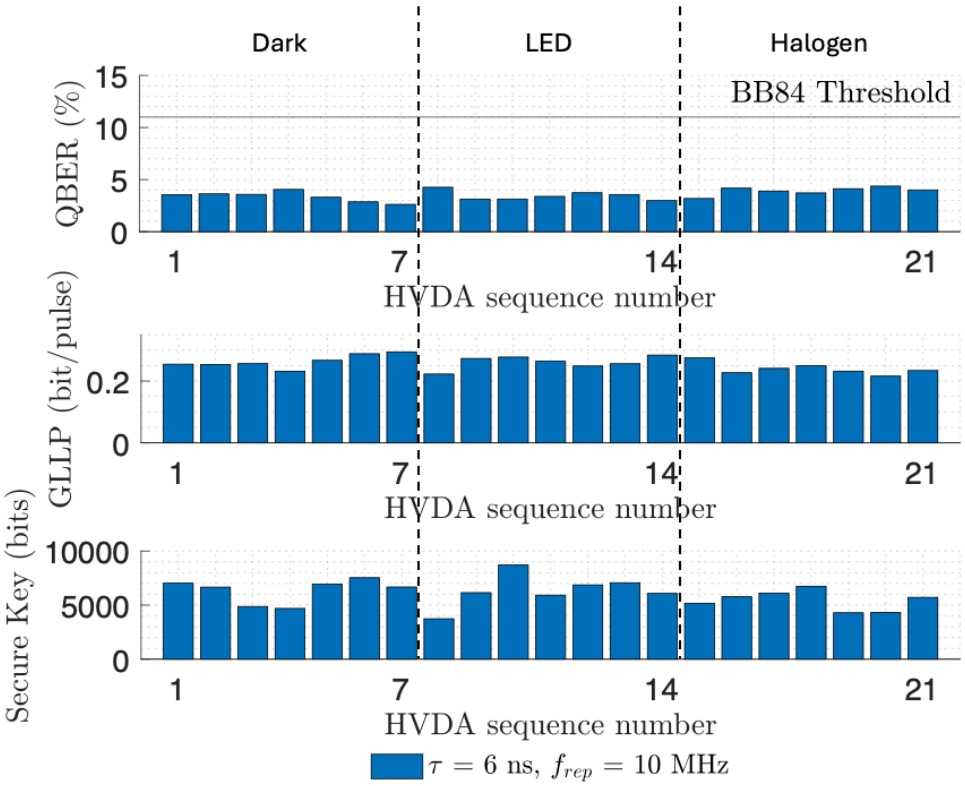


Figure 9: 30 minute experiment with a QKD system that operated at 10 MHz repetition rate with a 6 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp. This is equivalent to 7 HVDA sequences in darkness, 7 sequences under LED lighting, and 7 sequences under halogen lamp. Each iteration in the experiment (1 HVDA sequence) was sampled at 84 seconds. The QBER, GLLP secure key rate, and the number of secure key bits were calculated for each HVDA sequence.

Table 9: Statistical analysis for the 30 minute experiment (10 MHz repetition rate and 6 ns gating window)

$f_{rep} = 10$ MHz, $\tau = 6$ ns	Total (30 min)	Dark (10 min)	LED (10 min)	Halogen (10 min)
Total signal counts K_μ^{sig}	497,148	167,871	169,729	159,548
Total error counts K_μ^{err}	18,387	5,833	6,026	6,528
Total counts in sifted basis $K_\mu^s = K_\mu^{sig} + K_\mu^{err}$	515,535	173,704	175,755	166,076
Average QBER (%) $E_{\mu,avg}$	3.58%	3.37%	3.46%	3.92%
Average GLLP (bit/pulse) $R_{GLLP,avg}$	0.255	0.264	0.261	0.239
Average error counts $\mu_{err} = E_{\mu,avg} \times K_\mu^{sig}$	17,798	5,657	5,873	6,254
Standard deviation of error counts $\sigma_{err} = \sqrt{\mu_{err}}$	133	75	77	79
Fluctuation in QBER (%) $\frac{\sigma_{err}}{K_\mu^{sig}} \times 100$	0.027%	0.045%	0.045%	0.05%
Total secure key bits $K_{secure} = R_{GLLP,avg} \times K_\mu^{sig}$	126,773	44,318	44,299	38,132

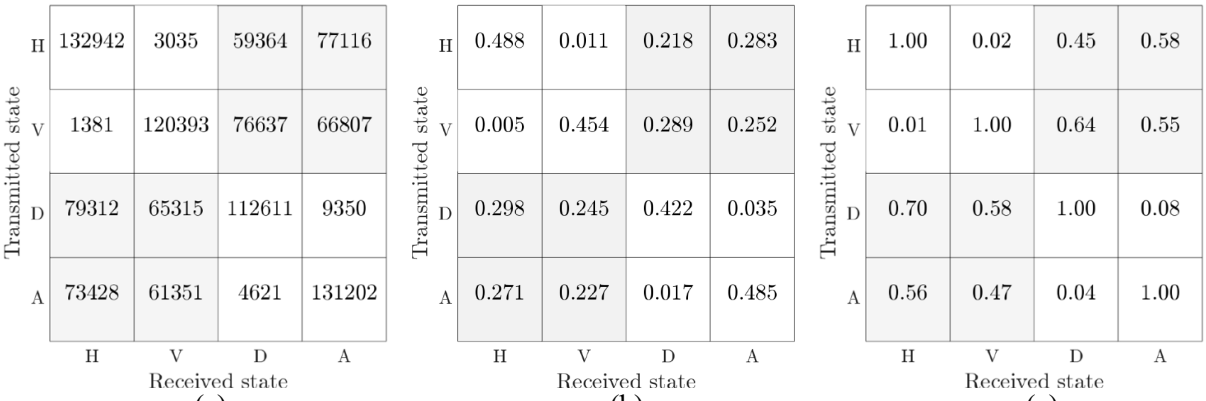


Figure 10: Crosstalk matrices for the 30 minute experiment with a QKD system that operated at 10 MHz repetition rate with a 6 ns gating window. Each matrix shows (a) the distribution of received photon counts across 30 minutes, (b) the ratio of received counts in each received state (column) relative to the total received counts per transmitted state (row), and (c) the normalisation of the received states (column) relative to the maximum received counts per transmitted state (row).

Table 10: Crosstalk polarisation error calculation

30 min (10 MHz, 6 ns)
$\left(e_{D/A}\middle\vert H\right) = 0.58 - 0.45 = 0.13$
$\left(e_{D/A}\middle\vert V\right) = 0.64 - 0.55 = 0.09$
$\left(e_{H/V}\middle\vert D\right) = 0.7 - 0.58 = 0.12$
$\left(e_{H/V}\middle\vert A\right) = 0.56 - 0.47 = 0.09$
$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.105$
$\Delta e = 0.11 - 0.105 = 0.005$

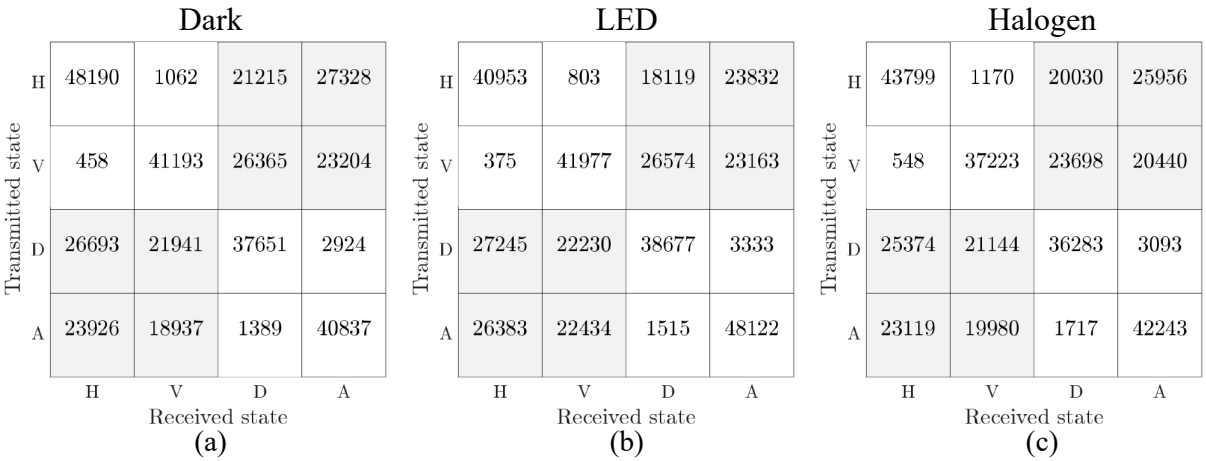


Figure 11: Crosstalk matrices that show the distribution of the received photon counts for the QKD system operated at 10 MHz repetition rate with a 6 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp.

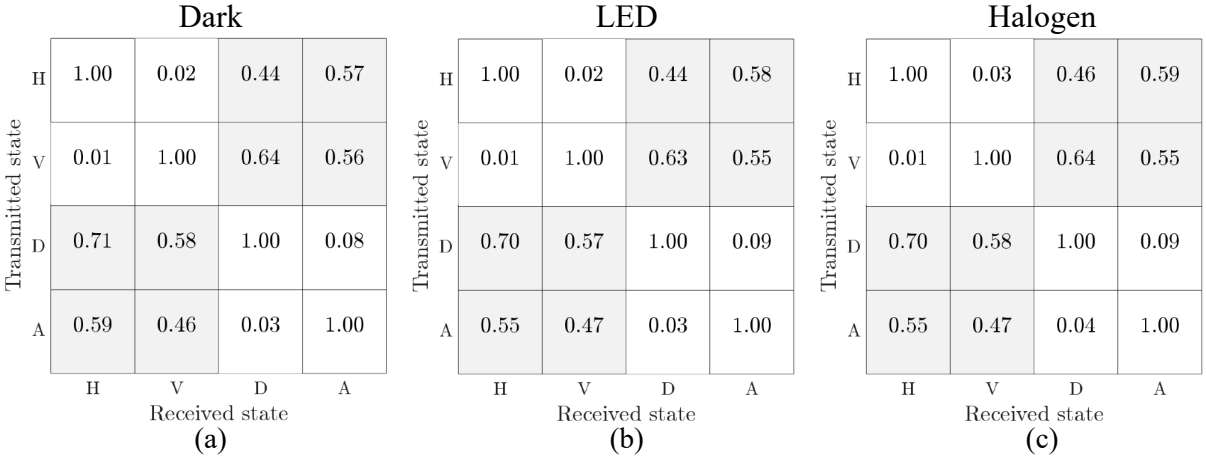


Figure 12: Normalised crosstalk matrices for the QKD system operated at 10 MHz repetition rate with a 6 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp. Each matrix was normalised for the received state (column) relative to the maximum received photon counts per transmitted state (row).

Table 11: Polarisation error calculation for the QKD system that ran for 30 minutes and operated at 10 MHz repetition rate with a 6 ns gating window. The errors were calculated for each ambient light scenario.

DARK (6 ns, 10 min)	LED (6 ns, 10 min)	HALOGEN (6 ns, 10 min)
$(e_{D/A}\|H) = 0.57 - 0.44 = 0.13$	$(e_{D/A}\|H) = 0.58 - 0.44 = 0.14$	$(e_{D/A}\|H) = 0.59 - 0.46 = 0.13$
$(e_{D/A}\|V) = 0.64 - 0.56 = 0.08$	$(e_{D/A}\|V) = 0.63 - 0.55 = 0.08$	$(e_{D/A}\|V) = 0.64 - 0.55 = 0.09$
$(e_{H/V}\|D) = 0.71 - 0.58 = 0.13$	$(e_{H/V}\|D) = 0.7 - 0.57 = 0.13$	$(e_{H/V}\|D) = 0.7 - 0.58 = 0.12$
$(e_{H/V}\|A) = 0.59 - 0.46 = 0.13$	$(e_{H/V}\|A) = 0.55 - 0.47 = 0.08$	$(e_{H/V}\|A) = 0.55 - 0.47 = 0.08$
$e_{D/A,avg} = 0.105$	$e_{D/A,avg} = 0.11$	$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.13$	$e_{H/V,avg} = 0.105$	$e_{H/V,avg} = 0.1$
$\Delta e = 0.13 - 0.105 = 0.025$	$\Delta e = 0.11 - 0.105 = 0.005$	$\Delta e = 0.11 - 0.1 = 0.01$

Table 12: Link budget analysis for the 30 minute experiment (10 MHz repetition rate and 6 ns gating window)

Number of HVDA sequences	7		
Repetition rate (assume one photon per pulse)	10×10^6		
Number of transmitter channels	4		
Total signal photons	**280,000,000**		
	Dark	**LED**	**Halogen**
Total received counts from transmitted H	97,795	83,707	90,955
Total received counts from transmitted V	91,220	92,089	81,909
Total received counts from transmitted D	89,209	91,485	85,894
Total received counts from transmitted A	85,089	98,454	87,059
Total received counts	**363,313**	**365,735**	**345,817**
Average dark counts per detector	500	500	500
Average dark counts across 4 detectors in one HVDA sequence	2,000	2,000	2,000
Average counts from LED lighting per detector	-	0	-
Average counts from LED lighting across 4 detectors in one HVDA sequence	-	0	-
Average counts from halogen lamp per detector	-	-	300
Average counts from halogen lamp across 4 detectors in one HVDA sequence	-	-	1,200
Average counts from noise sources per transmitted state in 7 HVDA sequences	14,000	14,000	22,400
Total counts from noise sources across all 4 transmitted states	56,000	56,000	89,600
Estimated total received signal counts	**307,313**	**309,735**	**256,217**
Total loss (ratio of received signal counts / transmitted signal photons)	1.097×10^{-3}	1.106×10^{-3}	9.15×10^{-4}
Total loss in dB	29.6 dB	29.56 dB	30.4 dB
Channel loss in dB	0 dB	0 dB	0 dB
Average transmittance across all 4 receiver channels	0.0064	0.0064	0.0064
Average receiver loss in dB	21.9 dB	21.9 dB	21.9 dB
Total loss – Average receiver loss in dB	**7.7 dB**	**7.66 dB**	**8.5 dB**
Estimated mean photon number	0.17	-	-

QKD system with 10 MHz repetition rate and 3 ns gating window

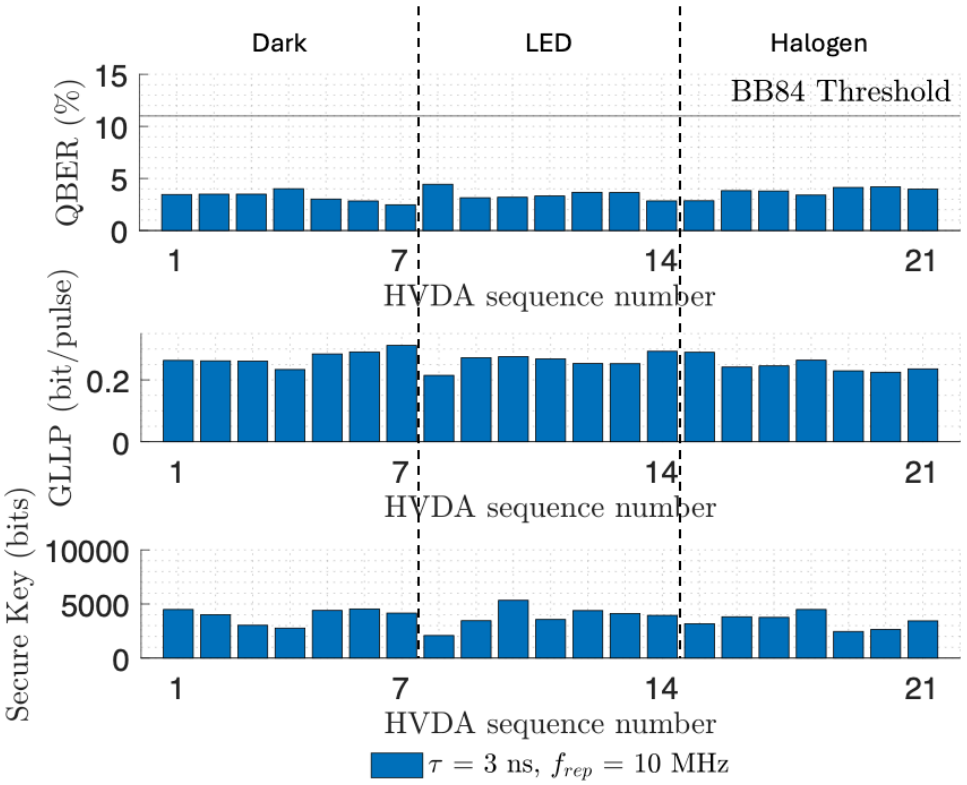


Figure 13: 30 minute experiment with a QKD system that operated at 10 MHz repetition rate with a 3 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp. This is equivalent to 7 HVDA sequences in darkness, 7 sequences under LED lighting, and 7 sequences under halogen lamp. Each iteration in the experiment (1 HVDA sequence) was sampled at 84 seconds. The QBER, GLLP secure key rate, and the number of secure key bits were calculated for each HVDA sequence.

Table 13: Statistical analysis for the 30 minute experiment (10 MHz repetition rate and 3 ns gating window)

$f_{rep} = 10$ MHz, $\tau = 3$ ns	Total (30 min)	Dark (10 min)	LED (10 min)	Halogen (10 min)
Total signal counts K_μ^{sig}	298,818	100,373	102,258	96,187
Total error counts K_μ^{err}	10,732	3,363	3,633	3,736
Total counts in sifted basis $K_\mu^s = K_\mu^{sig} + K_\mu^{err}$	309,550	103,736	105,891	99,923
Average QBER (%) $E_{\mu,avg}$	3.49%	3.26%	3.47%	3.74%
Average GLLP (bit/pulse) $R_{GLLP,avg}$	0.26	0.272	0.261	0.247
Average error counts $\mu_{err} = E_{\mu,avg} \times K_\mu^{sig}$	10,429	3,272	3,548	3,597
Standard deviation of error counts $\sigma_{err} = \sqrt{\mu_{err}}$	102	57	60	60
Fluctuation in QBER (%) $\frac{\sigma_{err}}{K_\mu^{sig}} \times 100$	0.034%	0.057%	0.059%	0.062%
Total secure key bits $K_{secure} = R_{GLLP,avg} \times K_\mu^{sig}$	77,693	27,302	26,689	23,758

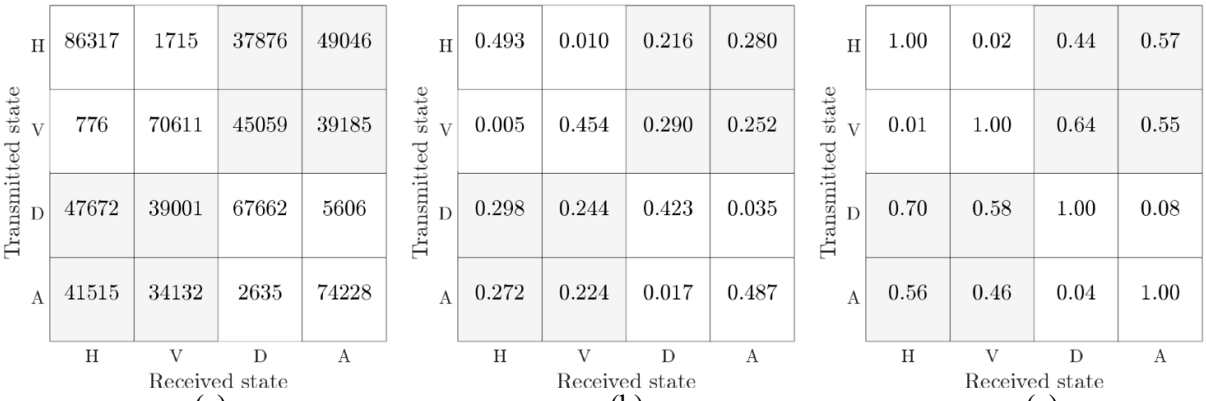


Figure 14: Crosstalk matrices for the 30 minute experiment with a QKD system that operated at 10 MHz repetition rate with a 3 ns gating window. Each matrix shows (a) the distribution of received photon counts across 30 minutes, (b) the ratio of received counts in each received state (column) relative to the total received counts per transmitted state (row), and (c) the normalisation of the received states (column) relative to the maximum received counts per transmitted state (row).

Table 14: Crosstalk polarisation error calculation

30 min (10 MHz, 3 ns)
$\left(e_{D/A}\middle\vert H\right) = 0.57 - 0.44 = 0.13$
$\left(e_{D/A}\middle\vert V\right) = 0.64 - 0.55 = 0.09$
$\left(e_{H/V}\middle\vert D\right) = 0.7 - 0.58 = 0.12$
$\left(e_{H/V}\middle\vert A\right) = 0.56 - 0.46 = 0.1$
$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.11$
$\Delta e = 0.11 - 0.11 = 0$

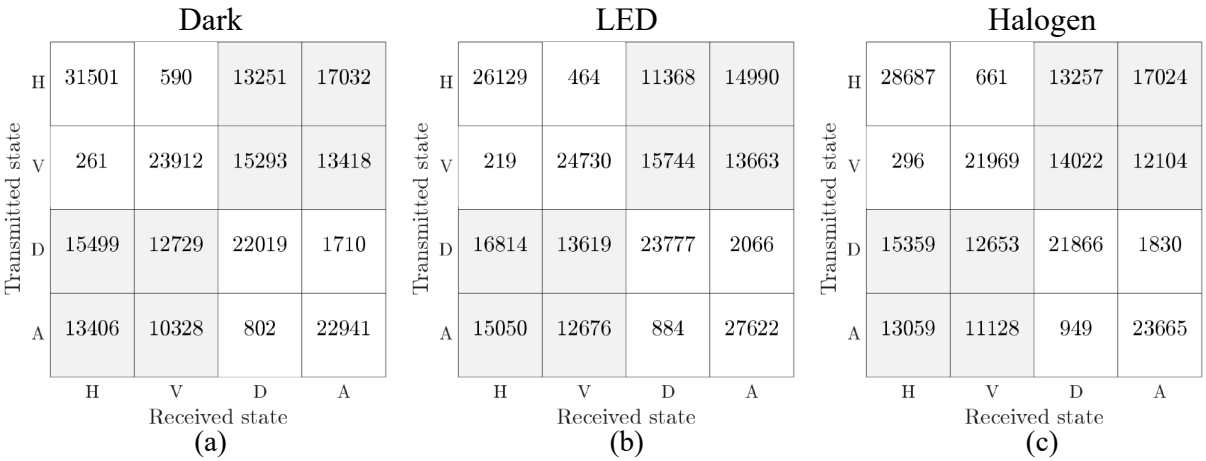


Figure 15: Crosstalk matrices that show the distribution of the received photon counts for the QKD system operated at 10 MHz repetition rate with a 3 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp.

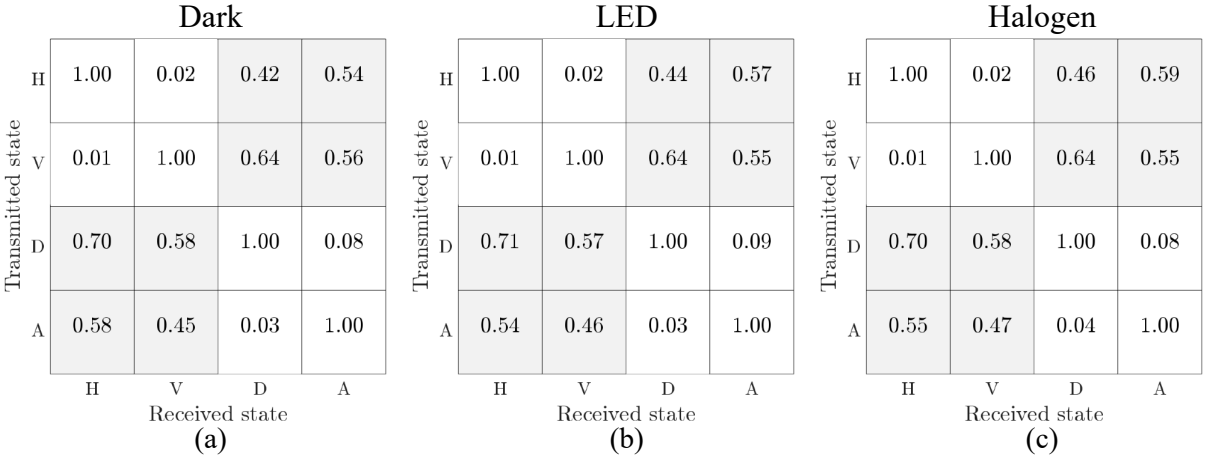


Figure 16: Normalised crosstalk matrices for the QKD system operated at 10 MHz repetition rate with a 3 ns gating window. The experiment ran for 30 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 10 minutes under a halogen lamp. Each matrix was normalised for the received state (column) relative to the maximum received photon counts per transmitted state (row).

Table 15: Polarisation error calculation for the QKD system that ran for 30 minutes and operated at 10 MHz repetition rate with a 3 ns gating window. The errors were calculated for each ambient light scenario.

DARK (3 ns, 10 min)	LED (3 ns, 10 min)	HALOGEN (3 ns, 10 min)
$(e_{D/A}\|H) = 0.54 - 0.42 = 0.12$	$(e_{D/A}\|H) = 0.57 - 0.44 = 0.13$	$(e_{D/A}\|H) = 0.59 - 0.46 = 0.13$
$(e_{D/A}\|V) = 0.64 - 0.56 = 0.08$	$(e_{D/A}\|V) = 0.64 - 0.55 = 0.09$	$(e_{D/A}\|V) = 0.64 - 0.55 = 0.09$
$(e_{H/V}\|D) = 0.7 - 0.58 = 0.12$	$(e_{H/V}\|D) = 0.71 - 0.57 = 0.14$	$(e_{H/V}\|D) = 0.7 - 0.58 = 0.12$
$(e_{H/V}\|A) = 0.58 - 0.45 = 0.13$	$(e_{H/V}\|A) = 0.54 - 0.46 = 0.08$	$(e_{H/V}\|A) = 0.55 - 0.47 = 0.08$
$e_{D/A,avg} = 0.1$	$e_{D/A,avg} = 0.11$	$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.125$	$e_{H/V,avg} = 0.11$	$e_{H/V,avg} = 0.1$
$\Delta e = 0.125 - 0.1 = 0.025$	$\Delta e = 0.11 - 0.11 = 0$	$\Delta e = 0.11 - 0.1 = 0.01$

Table 16: Link budget analysis for the 30 minute experiment (10 MHz repetition rate and 3 ns gating window)

Number of HVDA sequences	7		
Repetition rate (assume one photon per pulse)	10×10^6		
Number of transmitter channels	4		
Total signal photons	**280,000,000**		
	Dark	**LED**	**Halogen**
Total received counts from transmitted H	62,374	52,951	59,629
Total received counts from transmitted V	52,884	54,356	48,391
Total received counts from transmitted D	51,957	56,276	51,708
Total received counts from transmitted A	47,477	56,232	48,801
Total received counts	**214,692**	**219,815**	**208,529**
Average dark counts per detector	500	500	500
Average dark counts across 4 detectors in one HVDA sequence	2,000	2,000	2,000
Average counts from LED lighting per detector	-	0	-
Average counts from LED lighting across 4 detectors in one HVDA sequence	-	0	-
Average counts from halogen lamp per detector	-	-	300
Average counts from halogen lamp across 4 detectors in one HVDA sequence	-	-	1,200
Average counts from noise sources per transmitted state in 7 HVDA sequences	14,000	14,000	22,400
Total counts from noise sources across all 4 transmitted states	56,000	56,000	89,600
Estimated total received signal counts	**158,692**	**163,815**	**118,929**
Total loss (ratio of received signal counts / transmitted signal photons)	5.67×10^{-4}	5.85×10^{-4}	4.25×10^{-4}
Total loss in dB	32.5 dB	32.3 dB	33.7 dB
Channel loss in dB	0 dB	0 dB	0 dB
Average transmittance across all 4 receiver channels	0.0064	0.0064	0.0064
Average receiver loss in dB	21.9 dB	21.9 dB	21.9 dB
Total loss – Average receiver loss in dB	**10.6 dB**	**10.4 dB**	**11.8 dB**

60 minute experiment

QKD system with 41.67 MHz repetition rate and 6 ns gating window

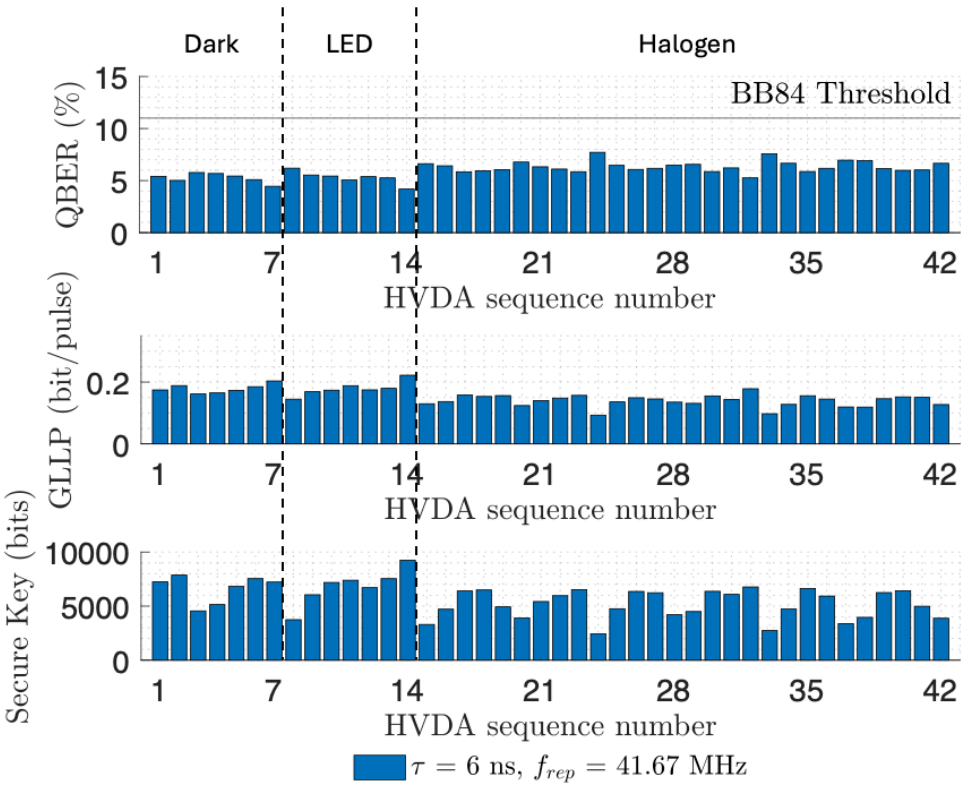


Figure 17: 60 minute experiment with a QKD system that operated at 41.67 MHz repetition rate with a 6 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp. This is equivalent to 7 HVDA sequences in darkness, 7 sequences under LED lighting, and 28 sequences under halogen lamp. Each iteration in the experiment (1 HVDA sequence) was sampled at 84 seconds. The QBER, GLLP secure key rate, and the number of secure key bits were calculated for each HVDA sequence.

Table 17: Statistical analysis for the 60 minute experiment (41.67 MHz repetition rate and 6 ns gating window)

$f_{rep} = 41.67$ MHz, $\tau = 6$ ns	Total (60 min)	Dark (10 min)	LED (10 min)	Halogen (40 min)
Total signal counts K_μ^{sig}	1,541,866	258,458	264,405	1,019,003
Total error counts K_μ^{err}	97,335	14,303	14,608	68,424
Total counts in sifted basis $K_\mu^s = K_\mu^{sig} + K_\mu^{err}$	1,639,201	272,761	279,013	1,087,427
Average QBER (%) $E_{\mu,avg}$	5.99%	5.27%	5.29%	6.35%
Average GLLP (bit/pulse) $R_{GLLP,avg}$	0.153	0.179	0.179	0.14
Average error counts $\mu_{err} = E_{\mu,avg} \times K_\mu^{sig}$	92,358	13,621	13,987	64,707
Standard deviation of error counts $\sigma_{err} = \sqrt{\mu_{err}}$	304	117	118	254
Fluctuation in QBER (%) $\frac{\sigma_{err}}{K_\mu^{sig}} \times 100$	0.02%	0.045%	0.045%	0.025%
Total secure key bits $K_{secure} = R_{GLLP,avg} \times K_\mu^{sig}$	235,906	46,264	47,329	142,660

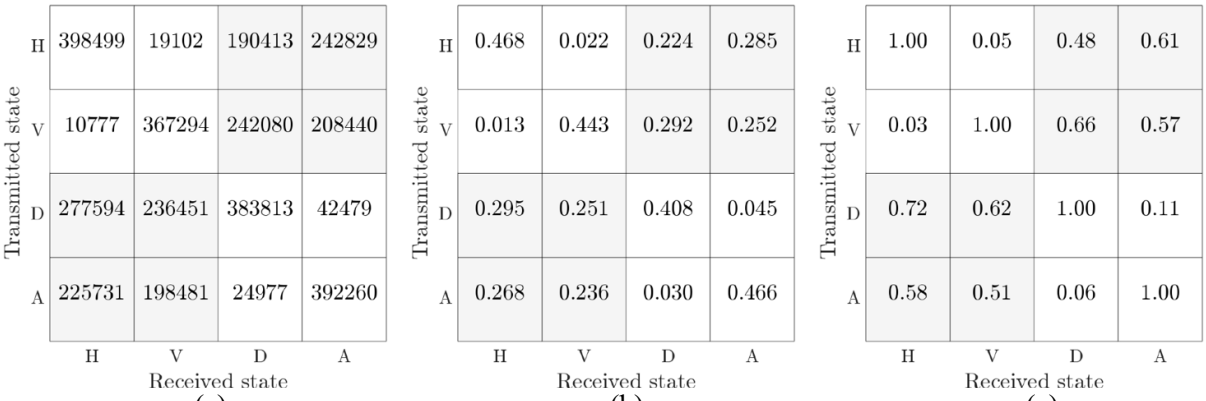


Figure 18: Crosstalk matrices for the 60 minute experiment with a QKD system that operated at 41.67 MHz repetition rate with a 6 ns gating window. Each matrix shows (a) the distribution of received photon counts across 60 minutes, (b) the ratio of received counts in each received state (column) relative to the total received counts per transmitted state (row), and (c) the normalisation of the received states (column) relative to the maximum received counts per transmitted state (row).

Table 18: Crosstalk polarisation error calculation

60 min (41.67 MHz, 6 ns)
$\left(e_{D/A}\middle\vert H\right) = 0.61 - 0.48 = 0.13$
$\left(e_{D/A}\middle\vert V\right) = 0.66 - 0.57 = 0.09$
$\left(e_{H/V}\middle\vert D\right) = 0.72 - 0.62 = 0.1$
$\left(e_{H/V}\middle\vert A\right) = 0.58 - 0.51 = 0.07$
$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.085$
$\Delta e = 0.11 - 0.085 = 0.025$

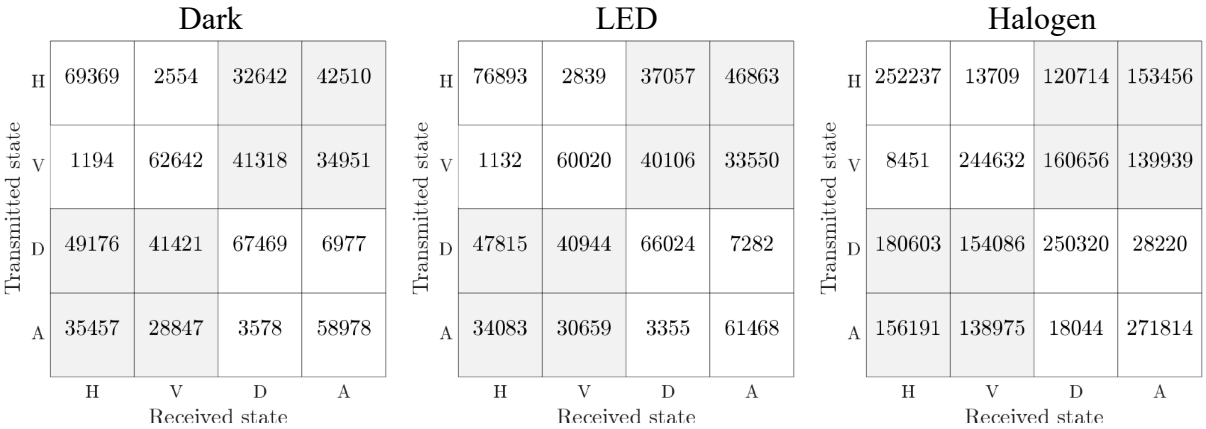


Figure 19: Crosstalk matrices that show the distribution of the received photon counts for the QKD system operated at 41.67 MHz repetition rate with a 6 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp.

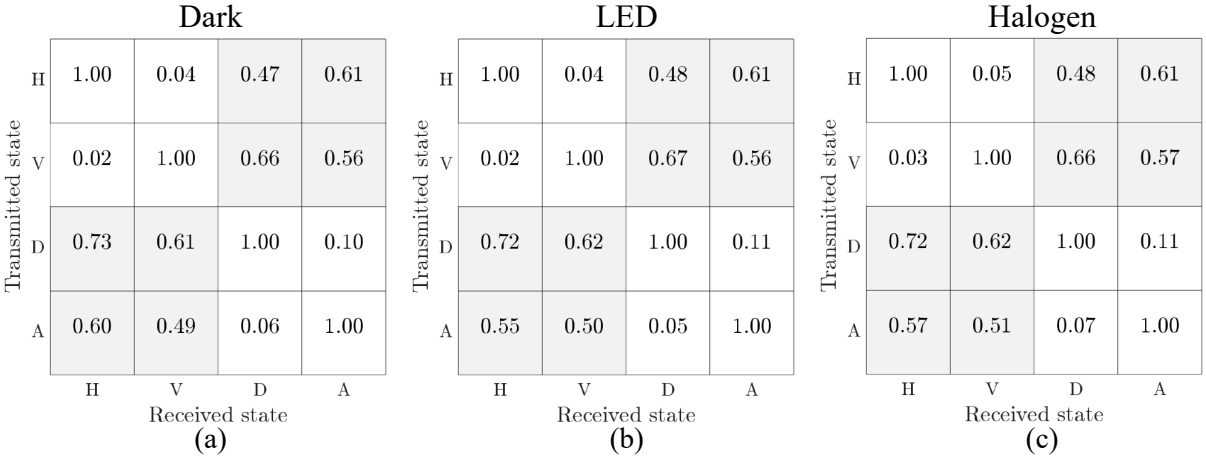


Figure 20: Normalised crosstalk matrices for the QKD system operated at 41.67 MHz repetition rate with a 6 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp. Each matrix was normalised for the received state (column) relative to the maximum received photon counts per transmitted state (row).

Table 19: Polarisation error calculation for the QKD system that ran for 60 minutes and operated at 41.67 MHz repetition rate with a 6 ns gating window. The errors were calculated for each ambient light scenario.

DARK (6 ns, 10min)	LED (6 ns, 10 min)	HALOGEN (6 ns, 40 min)
$(e_{D/A}\|H) = 0.61 - 0.47 = 0.14$	$(e_{D/A}\|H) = 0.61 - 0.48 = 0.13$	$(e_{D/A}\|H) = 0.61 - 0.48 = 0.13$
$(e_{D/A}\|V) = 0.66 - 0.56 = 0.1$	$(e_{D/A}\|V) = 0.67 - 0.56 = 0.11$	$(e_{D/A}\|V) = 0.66 - 0.57 = 0.09$
$(e_{H/V}\|D) = 0.73 - 0.61 = 0.12$	$(e_{H/V}\|D) = 0.72 - 0.62 = 0.1$	$(e_{H/V}\|D) = 0.72 - 0.62 = 0.1$
$(e_{H/V}\|A) = 0.6 - 0.49 = 0.11$	$(e_{H/V}\|A) = 0.55 - 0.5 = 0.05$	$(e_{H/V}\|A) = 0.57 - 0.51 = 0.06$
$e_{D/A,avg} = 0.12$	$e_{D/A,avg} = 0.12$	$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.115$	$e_{H/V,avg} = 0.075$	$e_{H/V,avg} = 0.08$
$\Delta e = 0.12 - 0.115 = 0.005$	$\Delta e = 0.12 - 0.075 = 0.045$	$\Delta e = 0.11 - 0.08 = 0.03$

Table 20: Link budget analysis for the 60 minute experiment (41.67 MHz repetition rate and 6 ns gating window)

Number of HVDA sequences	7		
Repetition rate (assume one photon per pulse)	41.67×10^6		
Number of transmitter channels	4		
Total signal photons	**1,166,760,000**		
	Dark	**LED**	**Halogen (1/4 total received counts)**
Total received counts from transmitted H	147,075	163,652	135,029
Total received counts from transmitted V	140,105	134,808	138,420
Total received counts from transmitted D	165,043	162,065	153,308
Total received counts from transmitted A	126,860	129,565	146,257
Total received counts	**579,083**	**590,090**	**573,014**
Average dark counts per detector	500	500	500
Average dark counts across 4 detectors in one HVDA sequence	2,000	2,000	2,000
Average counts from LED lighting per detector	-	0	-
Average counts from LED lighting across 4 detectors in one HVDA sequence	-	0	-
Average counts from halogen lamp per detector	-	-	300
Average counts from halogen lamp across 4 detectors in one HVDA sequence	-	-	1,200
Average counts from noise sources per transmitted state in 7 HVDA sequences	14,000	14,000	22,400
Total counts from noise sources across all 4 transmitted states	56,000	56,000	89,600
Estimated total received signal counts	**523,083**	**534,090**	**483,414**
Total loss (ratio of received signal counts / transmitted signal photons)	4.48×10^{-4}	4.58×10^{-4}	4.14×10^{-4}
Total loss in dB	33.5 dB	33.4 dB	33.8 dB
Channel loss in dB	0 dB	0 dB	0 dB
Average transmittance across all 4 receiver channels	0.0064	0.0064	0.0064
Average receiver loss in dB	21.9 dB	21.9 dB	21.9 dB
Total loss – Average receiver loss in dB	**11.6 dB**	**11.5 dB**	**11.9 dB**
Estimated mean photon number	0.069	-	-

QKD system with 41.67 MHz repetition rate and 3 ns gating window

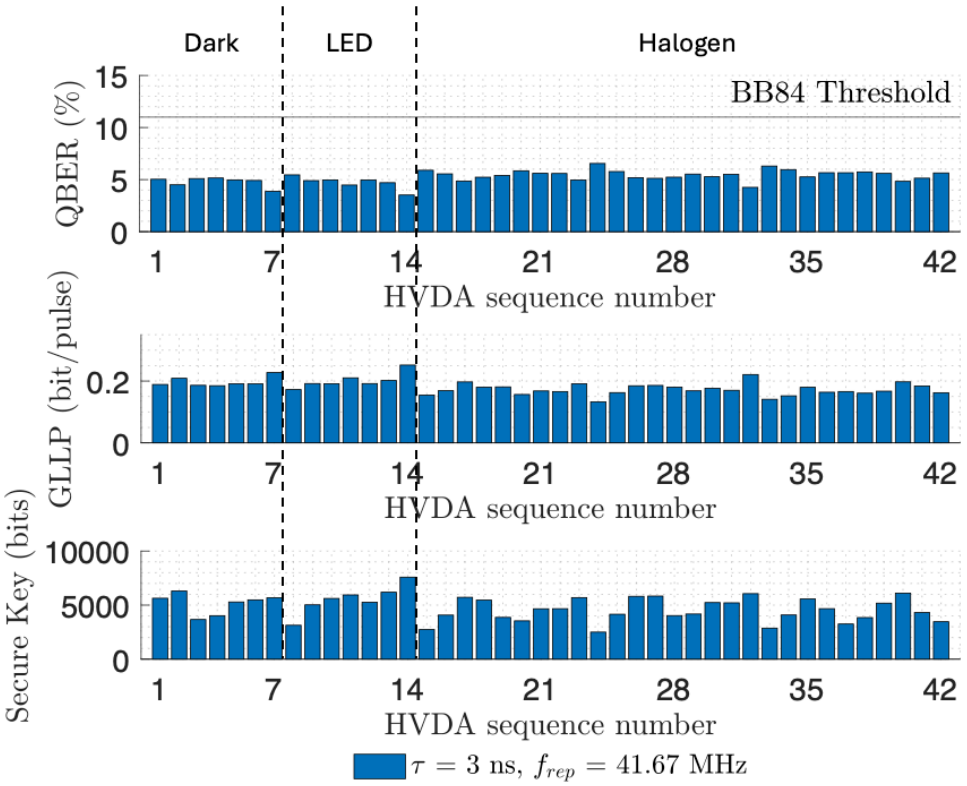
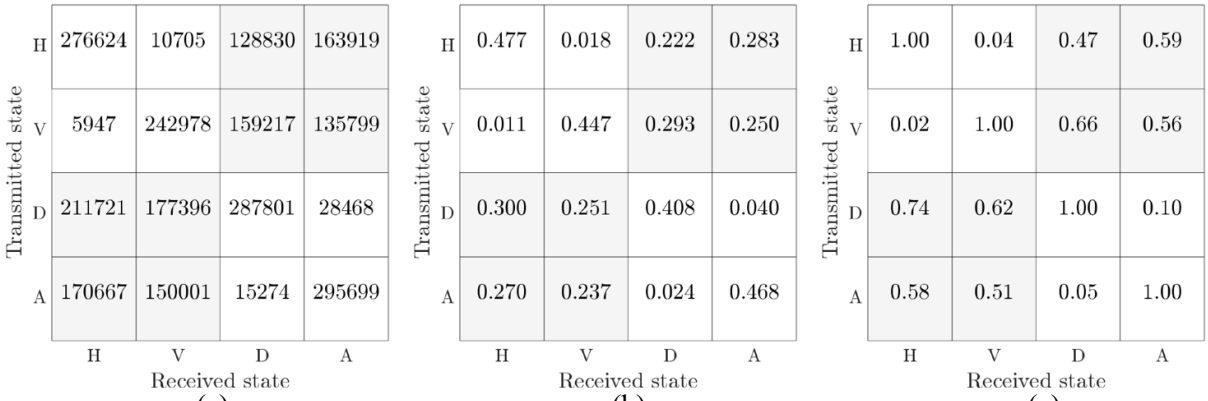


Figure 21: 60 minute experiment with a QKD system that operated at 41.67 MHz repetition rate with a 3 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp. This is equivalent to 7 HVDA sequences in darkness, 7 sequences under LED lighting, and 28 sequences under halogen lamp. Each iteration in the experiment (1 HVDA sequence) was sampled at 84 seconds. The QBER, GLLP secure key rate, and the number of secure key bits were calculated for each HVDA sequence.

Table 21: Statistical analysis for the 60 minute experiment (41.67 MHz repetition rate and 3 ns gating window)

$f_{rep} = 41.67$ MHz, $\tau = 3$ ns	Total (60 min)	Dark (10 min)	LED (10 min)	Halogen (40 min)
Total signal counts K_μ^{sig}	1,103,102	182,877	190,205	730,020
Total error counts K_μ^{err}	60,394	9,185	9,302	41,907
Total counts in sifted basis $K_\mu^s = K_\mu^{sig} + K_\mu^{err}$	1,163,496	192,062	199,507	771,927
Average QBER (%) $E_{\mu,avg}$	5.23%	4.79%	4.71%	5.47%
Average GLLP (bit/pulse) $R_{GLLP,avg}$	0.181	0.197	0.202	0.172
Average error counts $\mu_{err} = E_{\mu,avg} \times K_\mu^{sig}$	57,692	8,760	8,959	39,932
Standard deviation of error counts $\sigma_{err} = \sqrt{\mu_{err}}$	240	94	95	200
Fluctuation in QBER (%) $\frac{\sigma_{err}}{K_\mu^{sig}} \times 100$	0.022%	0.051%	0.05%	0.027%
Total secure key bits $K_{secure} = R_{GLLP,avg} \times K_\mu^{sig}$	199,662	36,027	38,421	125,563



Transmitted state \ Received state	H	V	D	A
H	276624	10705	128830	163919
V	5947	242978	159217	135799
D	211721	177396	287801	28468
A	170667	150001	15274	295699

(a)

Transmitted state \ Received state	H	V	D	A
H	0.477	0.018	0.222	0.283
V	0.011	0.447	0.293	0.250
D	0.300	0.251	0.408	0.040
A	0.270	0.237	0.024	0.468

(b)

Transmitted state \ Received state	H	V	D	A
H	1.00	0.04	0.47	0.59
V	0.02	1.00	0.66	0.56
D	0.74	0.62	1.00	0.10
A	0.58	0.51	0.05	1.00

(c)

Figure 22: Crosstalk matrices for the 60 minute experiment with a QKD system that operated at 41.67 MHz repetition rate with a 3 ns gating window. Each matrix shows (a) the distribution of received photon counts across 60 minutes, (b) the ratio of received counts in each received state (column) relative to the total received counts per transmitted state (row), and (c) the normalisation of the received states (column) relative to the maximum received counts per transmitted state (row).

Table 22: Crosstalk polarisation error calculation

60 min (41.67 MHz, 3 ns)
$\left(e_{D/A}\middle\vert H\right) = 0.59 - 0.47 = 0.12$
$\left(e_{D/A}\middle\vert V\right) = 0.66 - 0.56 = 0.1$
$\left(e_{H/V}\middle\vert D\right) = 0.74 - 0.62 = 0.12$
$\left(e_{H/V}\middle\vert A\right) = 0.58 - 0.51 = 0.07$
$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.095$
$\Delta e = 0.11 - 0.095 = 0.015$

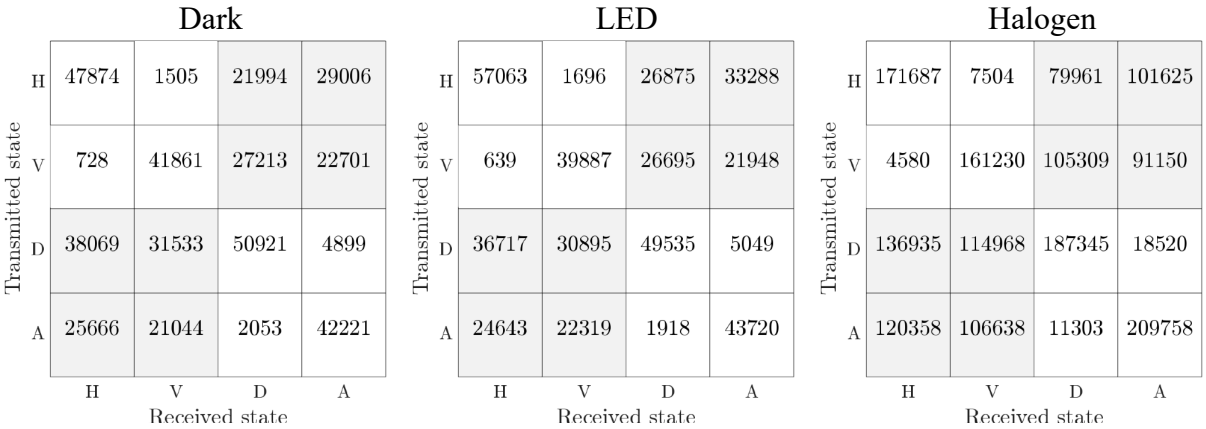


Figure 23: Crosstalk matrices that show the distribution of the received photon counts for the QKD system operated at 41.67 MHz repetition rate with a 3 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp.

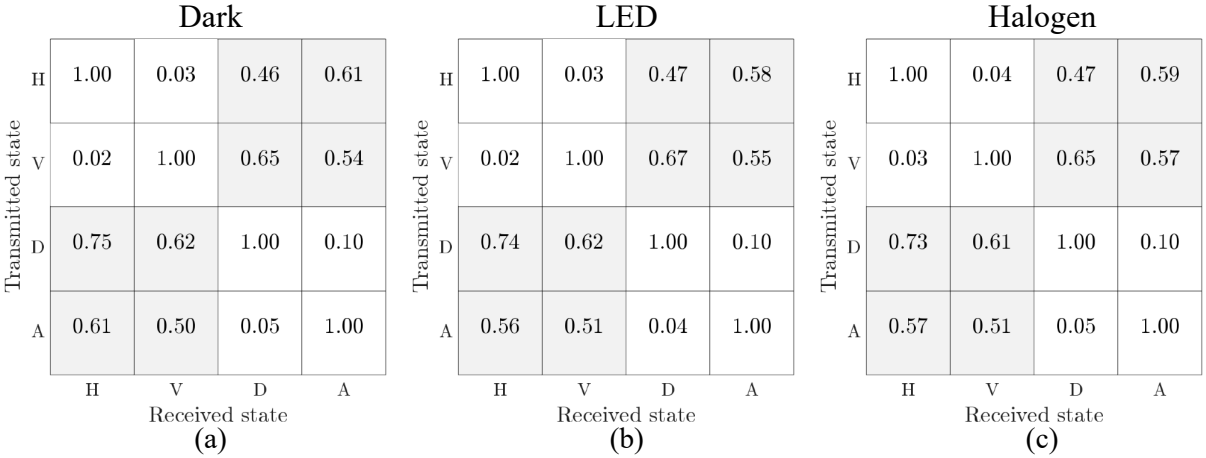


Figure 24: Normalised crosstalk matrices for the QKD system operated at 41.67 MHz repetition rate with a 3 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp. Each matrix was normalised for the received state (column) relative to the maximum received photon counts per transmitted state (row).

Table 23: Polarisation error calculation for the QKD system that ran for 60 minutes and operated at 41.67 MHz repetition rate with a 3 ns gating window. The errors were calculated for each ambient light scenario.

DARK (3 ns, 10 min)	LED (3 ns, 10 min)	HALOGEN (3 ns, 40 min)
$(e_{D/A}\|H) = 0.61 - 0.46 = 0.15$	$(e_{D/A}\|H) = 0.58 - 0.47 = 0.11$	$(e_{D/A}\|H) = 0.59 - 0.47 = 0.12$
$(e_{D/A}\|V) = 0.65 - 0.54 = 0.11$	$(e_{D/A}\|V) = 0.67 - 0.55 = 0.12$	$(e_{D/A}\|V) = 0.65 - 0.57 = 0.08$
$(e_{H/V}\|D) = 0.75 - 0.62 = 0.13$	$(e_{H/V}\|D) = 0.74 - 0.62 = 0.12$	$(e_{H/V}\|D) = 0.73 - 0.61 = 0.12$
$(e_{H/V}\|A) = 0.61 - 0.5 = 0.11$	$(e_{H/V}\|A) = 0.56 - 0.51 = 0.05$	$(e_{H/V}\|A) = 0.57 - 0.51 = 0.06$
$e_{D/A,avg} = 0.13$	$e_{D/A,avg} = 0.115$	$e_{D/A,avg} = 0.1$
$e_{H/V,avg} = 0.12$	$e_{H/V,avg} = 0.085$	$e_{H/V,avg} = 0.09$
$\Delta e = 0.13 - 0.12 = 0.01$	$\Delta e = 0.115 - 0.085 = 0.03$	$\Delta e = 0.1 - 0.09 = 0.01$

Table 24: Link budget analysis for the 60 minute experiment (41.67 MHz repetition rate and 3 ns gating window)

Number of HVDA sequences	7		
Repetition rate (assume one photon per pulse)	41.67×10^6		
Number of transmitter channels	4		
Total signal photons	**1,166,760,000**		
	Dark	**LED**	**Halogen (1/4 total received photons)**
Total received counts from transmitted H	100,379	118,922	90,194
Total received counts from transmitted V	92,503	89,169	90,568
Total received counts from transmitted D	125,422	122,196	114,442
Total received counts from transmitted A	90,984	92,600	112,016
Total received counts	**409,288**	**422,887**	**407,220**
Average dark counts per detector	500	500	500
Average dark counts across 4 detectors in one HVDA sequence	2,000	2,000	2,000
Average counts from LED lighting per detector	-	0	-
Average counts from LED lighting across 4 detectors in one HVDA sequence	-	0	-
Average counts from halogen lamp per detector	-	-	300
Average counts from halogen lamp across 4 detectors in one HVDA sequence	-	-	1,200
Average counts from noise sources per transmitted state in 7 HVDA sequences	14,000	14,000	22,400
Total counts from noise sources across all 4 transmitted states	56,000	56,000	89,600
Estimated total received signal counts	**353,288**	**366,887**	**317,620**
Total loss (ratio of received signal counts / transmitted signal photons)	3.03×10^{-4}	3.14×10^{-4}	2.72×10^{-4}
Total loss in dB	35.2 dB	35 dB	35.65 dB
Channel loss in dB	0 dB	0 dB	0 dB
Average transmittance across all 4 receiver channels	0.0064	0.0064	0.0064
Average receiver loss in dB	21.9 dB	21.9 dB	21.9 dB
Total loss – Average receiver loss in dB	**13.3 dB**	**13.1 dB**	**13.75 dB**

QKD system with 10 MHz repetition rate and 6 ns gating window

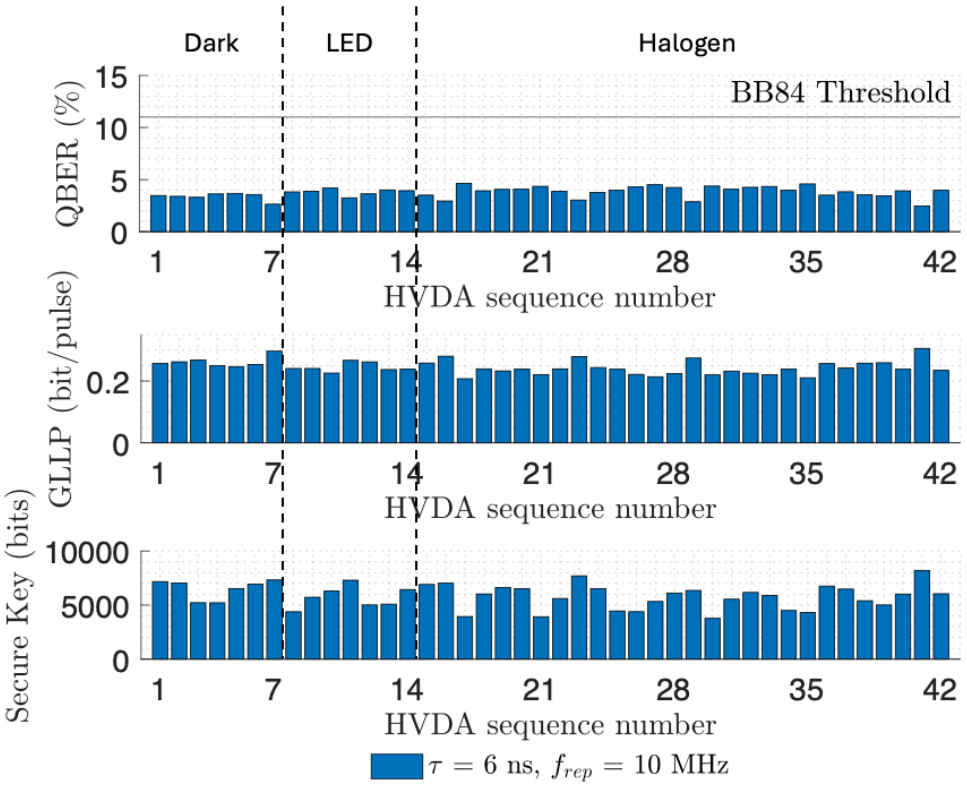


Figure 25: 60 minute experiment with a QKD system that operated at 10 MHz repetition rate with a 6 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp. This is equivalent to 7 HVDA sequences in darkness, 7 sequences under LED lighting, and 28 sequences under halogen lamp. Each iteration in the experiment (1 HVDA sequence) was sampled at 84 seconds. The QBER, GLLP secure key rate, and the number of secure key bits were calculated for each HVDA sequence.

Table 25: Statistical analysis for the 60 minute experiment (10 MHz repetition rate and 6 ns gating window)

$f_{rep} = 10$ MHz, $\tau = 6$ ns	Total (60 min)	Dark (10 min)	LED (10 min)	Halogen (40 min)
Total signal counts K_μ^{sig}	1,005,402	173,631	164,813	666,958
Total error counts K_μ^{err}	39,336	6,087	6,546	26,703
Total counts in sifted basis $K_\mu^s = K_\mu^{sig} + K_\mu^{err}$	1,044,738	179,718	171,359	693,661
Average QBER (%) $E_{\mu,avg}$	3.78%	3.38%	3.82%	3.87%
Average GLLP (bit/pulse) $R_{GLLP,avg}$	0.245	0.262	0.245	0.241
Average error counts $\mu_{err} = E_{\mu,avg} \times K_\mu^{sig}$	38,004	5,869	6,296	25,811
Standard deviation of error counts $\sigma_{err} = \sqrt{\mu_{err}}$	195	77	79	161
Fluctuation in QBER (%) $\frac{\sigma_{err}}{K_\mu^{sig}} \times 100$	0.019%	0.044%	0.048%	0.024%
Total secure key bits $K_{secure} = R_{GLLP,avg} \times K_\mu^{sig}$	246,324	45,491	40,379	160,737

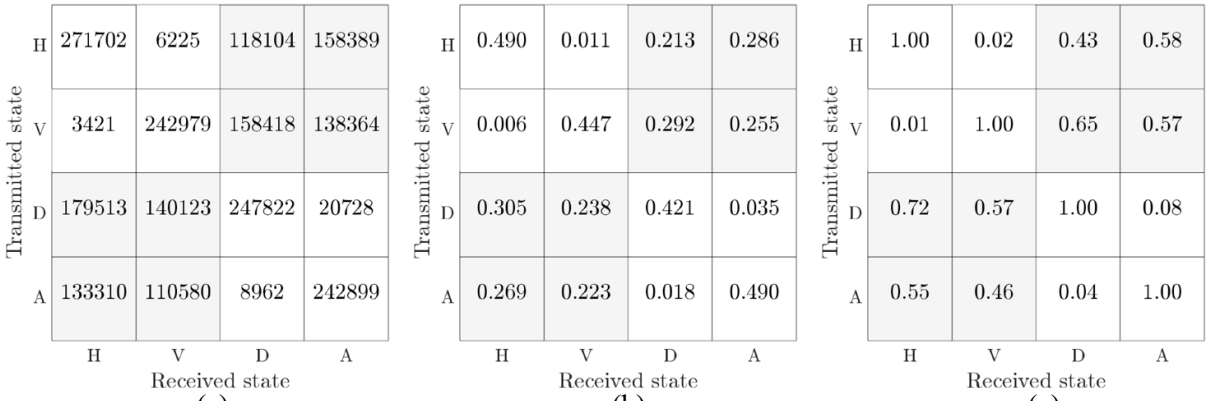


Figure 26: Crosstalk matrices for the 60 minute experiment with a QKD system that operated at 10 MHz repetition rate with a 6 ns gating window. Each matrix shows (a) the distribution of received photon counts across 60 minutes, (b) the ratio of received counts in each received state (column) relative to the total received counts per transmitted state (row), and (c) the normalisation of the received states (column) relative to the maximum received counts per transmitted state (row).

Table 26: Crosstalk polarisation error calculation

60 min (10 MHz, 6 ns)
$(e_{D/A}\|H) = 0.58 - 0.43 = 0.15$
$(e_{D/A}\|V) = 0.65 - 0.57 = 0.08$
$(e_{H/V}\|D) = 0.72 - 0.57 = 0.15$
$(e_{H/V}\|A) = 0.55 - 0.46 = 0.09$
$e_{D/A,avg} = 0.115$
$e_{H/V,avg} = 0.12$
$\Delta e = 0.12 - 0.115 = 0.005$

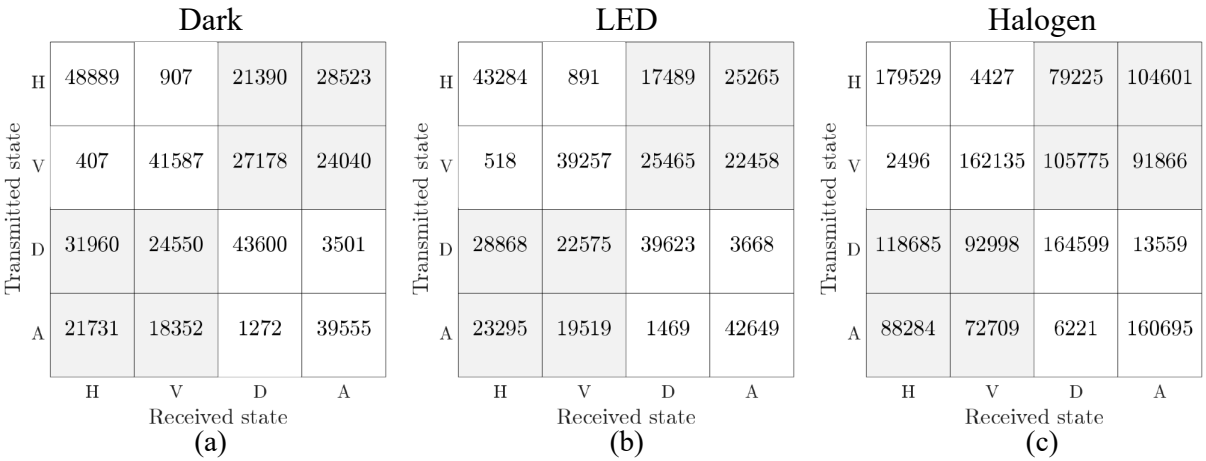


Figure 27: Crosstalk matrices that show the distribution of the received photon counts for the QKD system operated at 10 MHz repetition rate with a 6 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp.

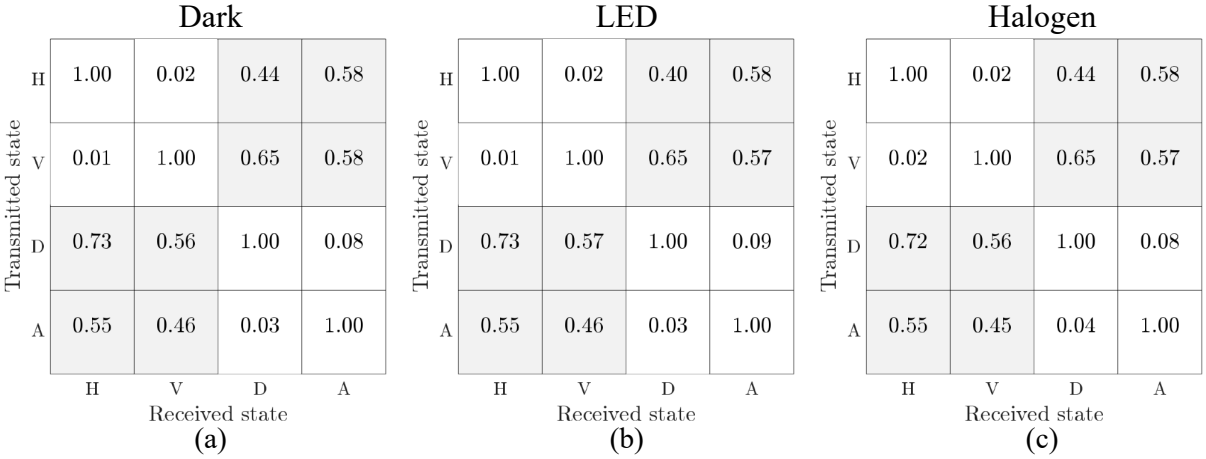


Figure 28: Normalised crosstalk matrices for the QKD system operated at 10 MHz repetition rate with a 6 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp. Each matrix was normalised for the received state (column) relative to the maximum received photon counts per transmitted state (row).

Table 27: Polarisation error calculation for the QKD system that ran for 60 minutes and operated at 10 MHz repetition rate with a 6 ns gating window. The errors were calculated for each ambient light scenario.

DARK (6 ns, 10 min)	LED (6 ns, 10 min)	HALOGEN (6 ns, 40 min)
$(e_{D/A}\|H) = 0.58 - 0.44 = 0.14$	$(e_{D/A}\|H) = 0.58 - 0.4 = 0.18$	$(e_{D/A}\|H) = 0.58 - 0.44 = 0.14$
$(e_{D/A}\|V) = 0.65 - 0.58 = 0.07$	$(e_{D/A}\|V) = 0.65 - 0.57 = 0.08$	$(e_{D/A}\|V) = 0.65 - 0.57 = 0.08$
$(e_{H/V}\|D) = 0.73 - 0.56 = 0.17$	$(e_{H/V}\|D) = 0.73 - 0.57 = 0.16$	$(e_{H/V}\|D) = 0.72 - 0.56 = 0.16$
$(e_{H/V}\|A) = 0.55 - 0.46 = 0.09$	$(e_{H/V}\|A) = 0.55 - 0.46 = 0.09$	$(e_{H/V}\|A) = 0.55 - 0.45 = 0.1$
$e_{D/A,avg} = 0.105$	$e_{D/A,avg} = 0.13$	$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.13$	$e_{H/V,avg} = 0.125$	$e_{H/V,avg} = 0.13$
$\Delta e = 0.13 - 0.105 = 0.025$	$\Delta e = 0.13 - 0.125 = 0.005$	$\Delta e = 0.13 - 0.11 = 0.02$

Table 28: Link budget analysis for 60 minute experiment (10 MHz repetition rate and 6 ns gating window)

Number of HVDA sequences	7		
Repetition rate (assume one photon per pulse)	10×10^6		
Number of transmitter channels	4		
Total signal photons	**280,000,000**		
	Dark	**LED**	**Halogen (1/4 total received photons)**
Total received counts from transmitted H	99,709	86,929	91,945
Total received counts from transmitted V	93,212	87,698	90,569
Total received counts from transmitted D	103,611	94,734	97,461
Total received counts from transmitted A	80,910	86,932	81,977
Total received counts	**377,442**	**356,293**	**361,952**
Average dark counts per detector	500	500	500
Average dark counts across 4 detectors in one HVDA sequence	2,000	2,000	2,000
Average counts from LED lighting per detector	-	0	-
Average counts from LED lighting across 4 detectors in one HVDA sequence	-	0	-
Average counts from halogen lamp per detector	-	-	300
Average counts from halogen lamp across 4 detectors in one HVDA sequence	-	-	1,200
Average counts from noise sources per transmitted state in 7 HVDA sequences	14,000	14,000	22,400
Total counts from noise sources across all 4 transmitted states	56,000	56,000	89,600
Estimated total received signal counts	**321,442**	**300,293**	**272,352**
Total loss (ratio of received signal counts / transmitted signal photons)	1.15×10^{-3}	1.07×10^{-3}	9.73×10^{-4}
Total loss in dB	29.4 dB	29.7 dB	30.1 dB
Channel loss in dB	0 dB	0 dB	0 dB
Average transmittance across all 4 receiver channels	0.0064	0.0064	0.0064
Average receiver loss in dB	21.9 dB	21.9 dB	21.9 dB
Total loss – Average receiver loss in dB	**7.5 dB**	**7.8 dB**	**8.2 dB**
Estimated mean photon number	0.18	-	-

QKD system with 10 MHz repetition rate and 3 ns gating window

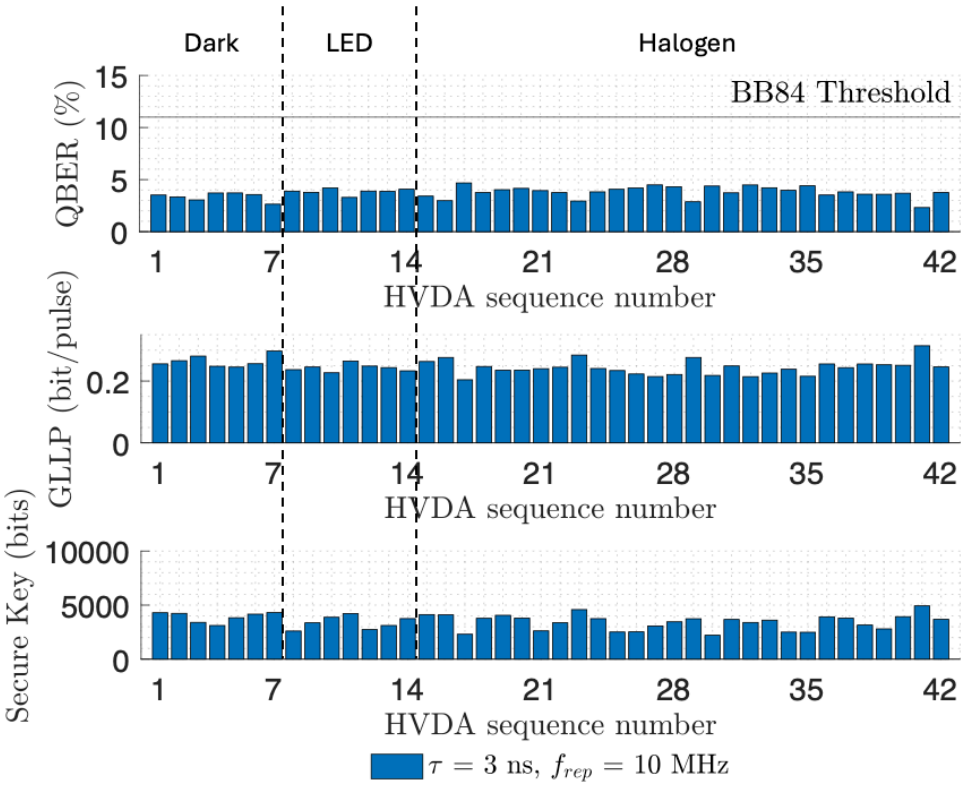


Figure 29: 60 minute experiment with a QKD system that operated at 10 MHz repetition rate with a 3 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp. This is equivalent to 7 HVDA sequences in darkness, 7 sequences under LED lighting, and 28 sequences under halogen lamp. Each iteration in the experiment (1 HVDA sequence) was sampled at 84 seconds. The QBER, GLLP secure key rate, and the number of secure key bits were calculated for each HVDA sequence.

Table 29: Statistical analysis for the 60 minute experiment (10 MHz repetition rate and 3 ns gating window)

$f_{rep} = 10$ MHz, $\tau = 3$ ns	Total (60 min)	Dark (10 min)	LED (10 min)	Halogen (40 min)
Total signal counts K_μ^{sig}	593,548	103,842	97,636	392,070
Total error counts K_μ^{err}	23,022	3,628	3,920	15,474
Total counts in sifted basis $K_\mu^s = K_\mu^{sig} + K_\mu^{err}$	616,570	107,470	101,556	407,544
Average QBER (%) $E_{\mu,avg}$	3.75%	3.36%	3.86%	3.82%
Average GLLP (bit/pulse) $R_{GLLP,avg}$	0.247	0.264	0.243	0.244
Average error counts $\mu_{err} = E_{\mu,avg} \times K_\mu^{sig}$	22,258	3,489	3,769	14,977
Standard deviation of error counts $\sigma_{err} = \sqrt{\mu_{err}}$	149	59	61	122
Fluctuation in QBER (%) $\frac{\sigma_{err}}{K_\mu^{sig}} \times 100$	0.025%	0.057%	0.062%	0.031%
Total secure key bits $K_{secure} = R_{GLLP,avg} \times K_\mu^{sig}$	146,606	27,414	23,726	95,665

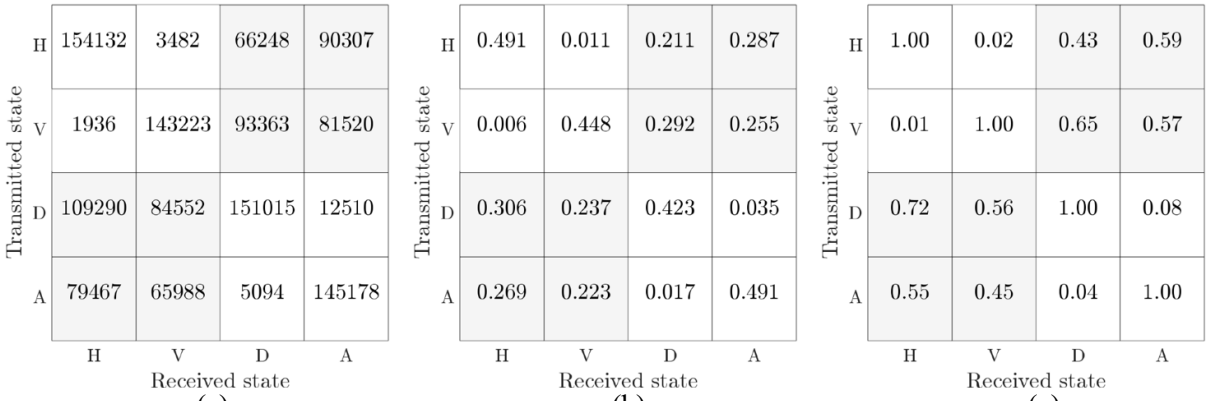


Figure 30: Crosstalk matrices for the 60 minute experiment with a QKD system that operated at 10 MHz repetition rate with a 3 ns gating window. Each matrix shows (a) the distribution of received photon counts across 60 minutes, (b) the ratio of received counts in each received state (column) relative to the total received counts per transmitted state (row), and (c) the normalisation of the received states (column) relative to the maximum received counts per transmitted state (row).

Table 30: Crosstalk polarisation error calculation

60 min (10 MHz, 3 ns)
$\left(e_{D/A}\middle\vert H\right) = 0.59 - 0.43 = 0.16$
$\left(e_{D/A}\middle\vert V\right) = 0.65 - 0.57 = 0.08$
$\left(e_{H/V}\middle\vert D\right) = 0.72 - 0.56 = 0.16$
$\left(e_{H/V}\middle\vert A\right) = 0.55 - 0.45 = 0.1$
$e_{D/A,avg} = 0.12$
$e_{H/V,avg} = 0.13$
$\Delta e = 0.13 - 0.12 = 0.01$

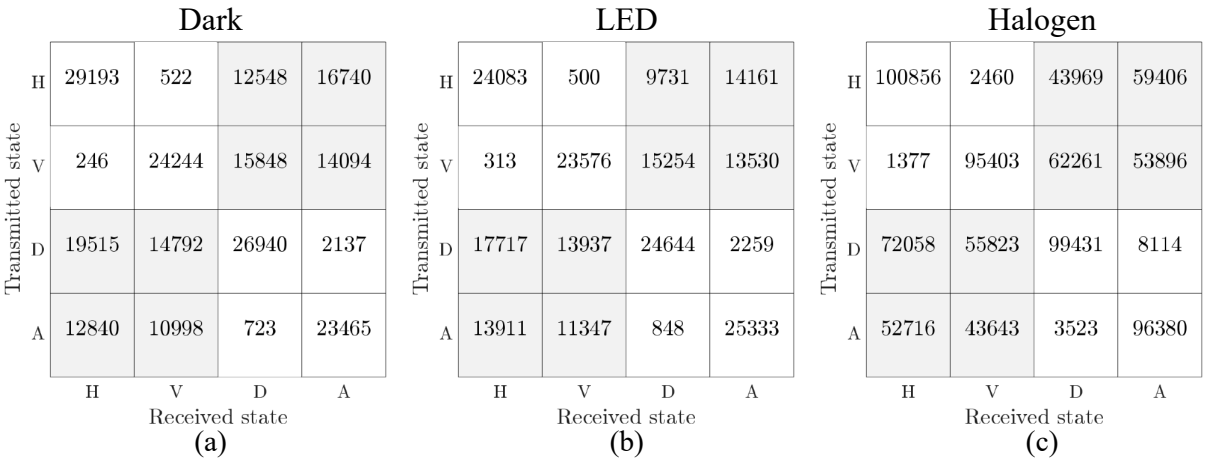


Figure 31: Crosstalk matrices that show the distribution of the received photon counts for the QKD system operated at 10 MHz repetition rate with a 3 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp.

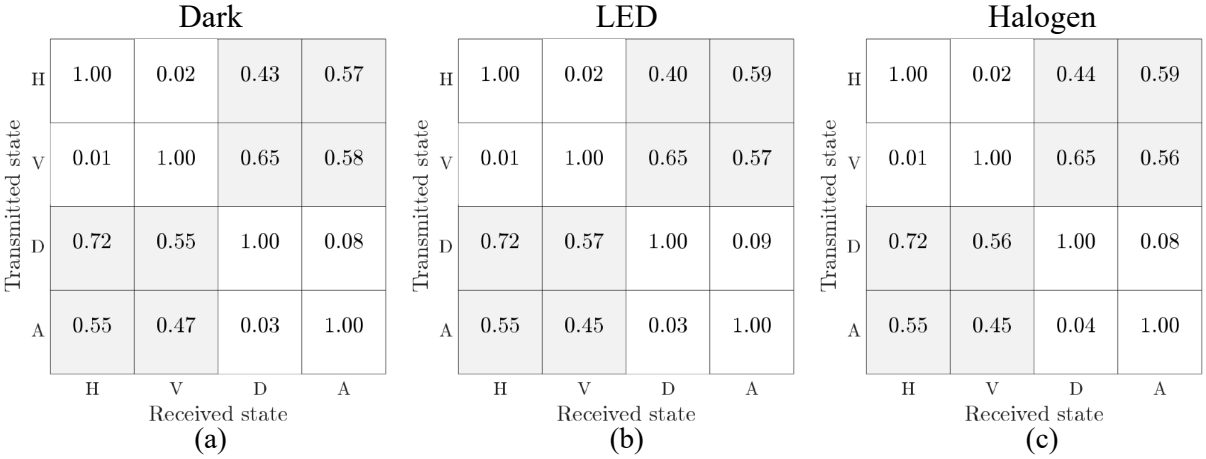


Figure 32: Normalised crosstalk matrices for the QKD system operated at 10 MHz repetition rate with a 3 ns gating window. The experiment ran for 60 minutes under ambient light conditions: (a) 10 minutes in darkness, (b) 10 minutes under LED lighting, and (c) 40 minutes under a halogen lamp. Each matrix was normalised for the received state (column) relative to the maximum received photon counts per transmitted state (row).

Table 31: Polarisation error calculation for the QKD system that ran for 60 minutes and operated at 10 MHz repetition rate with a 3 ns gating window. The errors were calculated for each ambient light scenario.

DARK (3 ns, 10 min)	LED (3 ns, 10 min)	HALOGEN (3 ns, 40 min)
$(e_{D/A}\|H) = 0.57 - 0.43 = 0.14$	$(e_{D/A}\|H) = 0.59 - 0.4 = 0.19$	$(e_{D/A}\|H) = 0.59 - 0.44 = 0.15$
$(e_{D/A}\|V) = 0.65 - 0.58 = 0.07$	$(e_{D/A}\|V) = 0.65 - 0.57 = 0.08$	$(e_{D/A}\|V) = 0.65 - 0.56 = 0.09$
$(e_{H/V}\|D) = 0.72 - 0.55 = 0.17$	$(e_{H/V}\|D) = 0.72 - 0.57 = 0.15$	$(e_{H/V}\|D) = 0.72 - 0.56 = 0.16$
$(e_{H/V}\|A) = 0.55 - 0.47 = 0.08$	$(e_{H/V}\|A) = 0.55 - 0.45 = 0.1$	$(e_{H/V}\|A) = 0.55 - 0.45 = 0.1$
$e_{D/A,avg} = 0.105$	$e_{D/A,avg} = 0.135$	$e_{D/A,avg} = 0.12$
$e_{H/V,avg} = 0.125$	$e_{H/V,avg} = 0.125$	$e_{H/V,avg} = 0.13$
$\Delta e = 0.125 - 0.105 = 0.02$	$\Delta e = 0.135 - 0.125 = 0.01$	$\Delta e = 0.13 - 0.12 = 0.01$

Table 32: Link budget analysis for the 60 minute experiment (10 MHz repetition rate and 3 ns gating window)

Number of HVDA sequences	7		
Repetition rate (assume one photon per pulse)	10×10^6		
Number of transmitter channels	4		
Total signal photons	**280,000,000**		
	Dark	**LED**	**Halogen (1/4 total received photons)**
Total received counts from transmitted H	59,003	48,475	51,673
Total received counts from transmitted V	54,432	52,673	53,234
Total received counts from transmitted D	63,384	58,557	58,858
Total received counts from transmitted A	48,026	51,439	49,066
Total received counts	**224,845**	**211,144**	**212,831**
Average dark counts per detector	500	500	500
Average dark counts across 4 detectors in one HVDA sequence	2,000	2,000	2,000
Average counts from LED lighting per detector	-	0	-
Average counts from LED lighting across 4 detectors in one HVDA sequence	-	0	-
Average counts from halogen lamp per detector	-	-	300
Average counts from halogen lamp across 4 detectors in one HVDA sequence	-	-	1,200
Average counts from noise sources per transmitted state in 7 HVDA sequences	14,000	14,000	22,400
Total counts from noise sources across all 4 transmitted states	56,000	56,000	89,600
Estimated total received signal counts	**168,845**	**155,144**	**123,231**
Total loss (ratio of received signal counts / transmitted signal photons)	6.03×10^{-4}	5.54×10^{-4}	4.4×10^{-4}
Total loss in dB	32.2 dB	32.56 dB	33.56 dB
Channel loss in dB	0 dB	0 dB	0 dB
Average transmittance across all 4 receiver channels	0.0064	0.0064	0.0064
Average receiver loss in dB	21.9 dB	21.9 dB	21.9 dB
Total loss – Average receiver loss in dB	**10.3 dB**	**10.66 dB**	**11.66 dB**

Crosstalk polarisation error calculations and normalised crosstalk matrices

30 minute experiment and 6 ns gating window

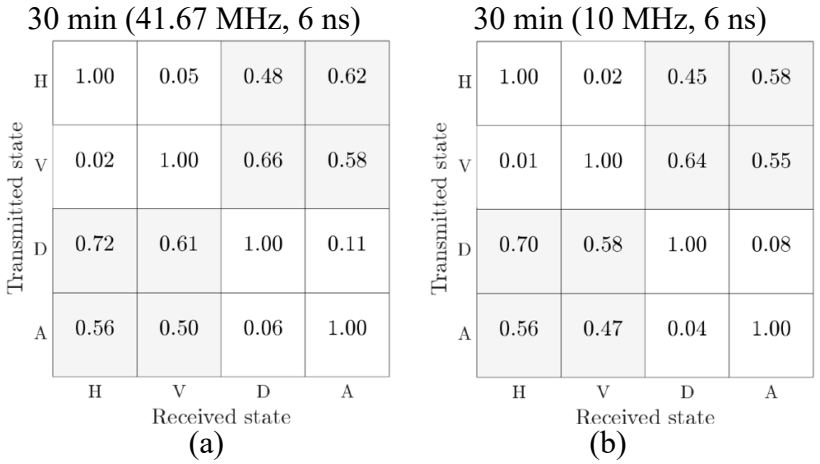


Figure 33: Normalised crosstalk matrices for the two 30 min experiments with a 6 ns gating window: (a) 41.67 MHz repetition rate and (b) 10 MHz repetition rate. Each received state was divided by the maximum received state in each row.

Table 33: Crosstalk polarisation error calculations for 30 min experiments operated at 41.67 MHz and 10 MHz repetition rates with a 6 ns gating window.

30 min (41.67 MHz, 6 ns)	30 min (10 MHz, 6 ns)
$(e_{D/A}\|H) = 0.62 - 0.48 = 0.14$	$(e_{D/A}\|H) = 0.58 - 0.45 = 0.13$
$(e_{D/A}\|V) = 0.66 - 0.58 = 0.08$	$(e_{D/A}\|V) = 0.64 - 0.55 = 0.09$
$(e_{H/V}\|D) = 0.72 - 0.61 = 0.11$	$(e_{H/V}\|D) = 0.7 - 0.58 = 0.12$
$(e_{H/V}\|A) = 0.56 - 0.5 = 0.06$	$(e_{H/V}\|A) = 0.56 - 0.47 = 0.09$
$e_{D/A,avg} = 0.11$	$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.085$	$e_{H/V,avg} = 0.105$
$\Delta e = 0.11 - 0.085 = 0.025$	$\Delta e = 0.11 - 0.105 = 0.005$

60 minute experiment and 6 ns gating window

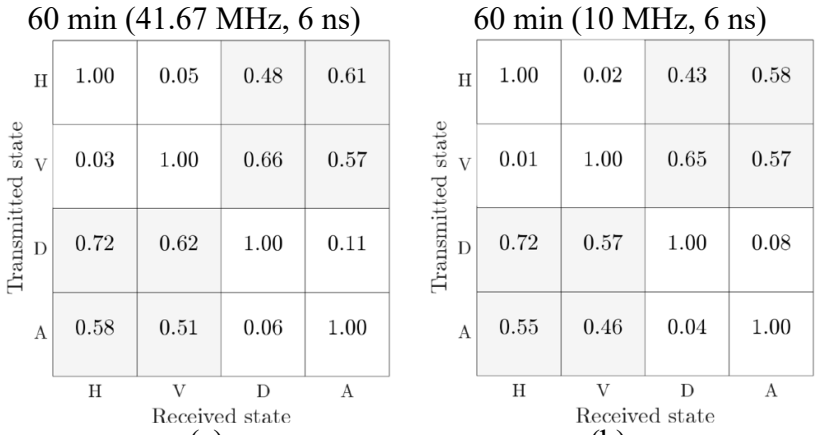


Figure 34: Normalised crosstalk matrices for the two 60 min experiments with a 6 ns gating window: (a) 41.67 MHz repetition rate and (b) 10 MHz repetition rate. Each received state was divided by the maximum received state in each row.

Table 34: Crosstalk polarisation error calculations for 60 min experiments operated at 41.67 MHz and 10 MHz repetition rates with a 6 ns gating window.

60 min (41.67 MHz, 6 ns)	60 min (10 MHz, 6 ns)
$(e_{D/A}\|H) = 0.61 - 0.48 = 0.13$	$(e_{D/A}\|H) = 0.58 - 0.43 = 0.15$
$(e_{D/A}\|V) = 0.66 - 0.57 = 0.09$	$(e_{D/A}\|V) = 0.65 - 0.57 = 0.08$
$(e_{H/V}\|D) = 0.72 - 0.62 = 0.1$	$(e_{H/V}\|D) = 0.72 - 0.57 = 0.15$
$(e_{H/V}\|A) = 0.58 - 0.51 = 0.07$	$(e_{H/V}\|A) = 0.55 - 0.46 = 0.09$
$e_{D/A,avg} = 0.11$	$e_{D/A,avg} = 0.115$
$e_{H/V,avg} = 0.085$	$e_{H/V,avg} = 0.12$
$\Delta e = 0.11 - 0.085 = 0.025$	$\Delta e = 0.12 - 0.115 = 0.005$

30 minute experiment and 3 ns gating window

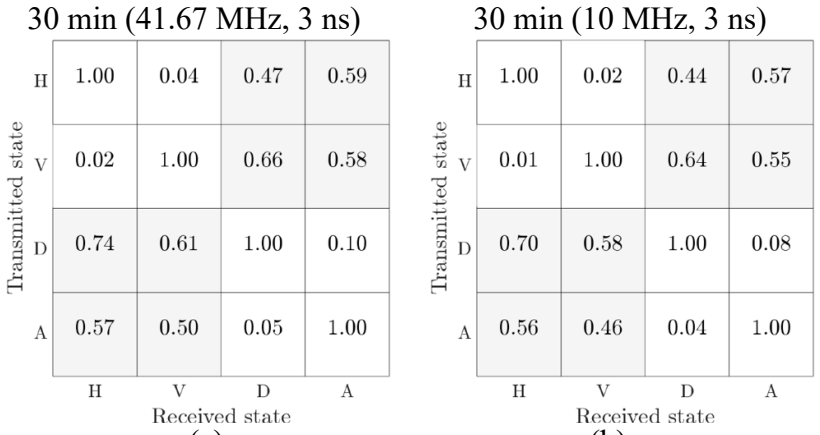


Figure 35: Normalised crosstalk matrices for the two 30 min experiments with a 3 ns gating window: (a) 41.67 MHz repetition rate and (b) 10 MHz repetition rate. Each received state was divided by the maximum received state in each row.

Table 35: Crosstalk polarisation error calculations for 30 min experiments operated at 41.67 MHz and 10 MHz repetition rates with a 3 ns gating window.

30 min (41.67 MHz, 3 ns)	30 min (10 MHz, 3 ns)
$(e_{D/A}\|H) = 0.59 - 0.47 = 0.12$	$(e_{D/A}\|H) = 0.57 - 0.44 = 0.13$
$(e_{D/A}\|V) = 0.66 - 0.58 = 0.08$	$(e_{D/A}\|V) = 0.64 - 0.55 = 0.09$
$(e_{H/V}\|D) = 0.74 - 0.61 = 0.13$	$(e_{H/V}\|D) = 0.7 - 0.58 = 0.12$
$(e_{H/V}\|A) = 0.57 - 0.5 = 0.07$	$(e_{H/V}\|A) = 0.56 - 0.46 = 0.1$
$e_{D/A,avg} = 0.1$	$e_{D/A,avg} = 0.11$
$e_{H/V,avg} = 0.1$	$e_{H/V,avg} = 0.11$
$\Delta e = 0.1 - 0.1 = 0$	$\Delta e = 0.11 - 0.11 = 0$

60 minute experiment and 3 ns gating window

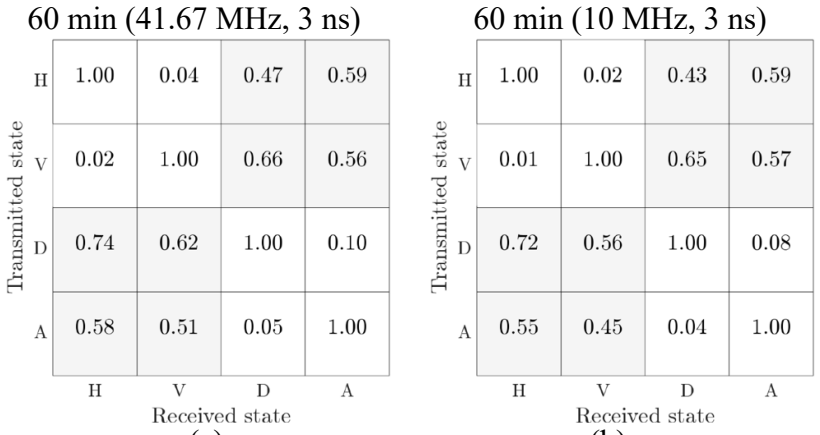


Figure 36: Normalised crosstalk matrices for the two 60 min experiments with a 3 ns gating window: (a) 41.67 MHz repetition rate and (b) 10 MHz repetition rate. Each received state was divided by the maximum received state in each row.

Table 36: Crosstalk polarisation error calculations for 60 min experiments operated at 41.67 MHz and 10 MHz repetition rates with a 3 ns gating window.

60 min (41.67 MHz, 3 ns)	60 min (10 MHz, 3 ns)
$(e_{D/A}\|H) = 0.59 - 0.47 = 0.12$	$(e_{D/A}\|H) = 0.59 - 0.43 = 0.16$
$(e_{D/A}\|V) = 0.66 - 0.56 = 0.1$	$(e_{D/A}\|V) = 0.65 - 0.57 = 0.08$
$(e_{H/V}\|D) = 0.74 - 0.62 = 0.12$	$(e_{H/V}\|D) = 0.72 - 0.56 = 0.16$
$(e_{H/V}\|A) = 0.58 - 0.51 = 0.07$	$(e_{H/V}\|A) = 0.55 - 0.45 = 0.1$
$e_{D/A,avg} = 0.11$	$e_{D/A,avg} = 0.12$
$e_{H/V,avg} = 0.095$	$e_{H/V,avg} = 0.13$
$\Delta e = 0.11 - 0.095 = 0.015$	$\Delta e = 0.13 - 0.12 = 0.01$