

Bidirectional Mitigation of Turbulence on Telescope Array with Optical Selection Combining

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ABSTRACT

A limiting factor for free-space optical (FSO) links is the deep fading of the received signal induced by atmospheric turbulence. One approach to mitigate fades is spatial diversity, which consists in transmitting data over several uncorrelated optical paths, decreasing the probability of a transmission failure after diversity combining. We present a proof-of-concept with a 4-telescope array coupled to single-mode fibers to provide spatial-diversity channels. The selection combining of the diversity channels is performed by means of an optical switch with switching time $< 1\mu\text{s}$. Measurements of received optical powers over 3 km demonstrate the potential of optical selection combining to mitigate FSO fades. One direct application where the switching times are negligible is quantum key distribution.

Keywords: FSO, spatial diversity, diversity combining, optical switch, reciprocity, QKD

1 INTRODUCTION

1.1 Current challenges of free-space optical (FSO) communication

FSO communication is a rapidly developing wireless technology that uses free space as the transmission medium, including the Earth's atmosphere for terrestrial and satellite feeder links. Two key advantages of FSO over radio-frequency (RF) communication are its higher potential throughput and less regulated spectrum. Unlike RF, the optical spectrum used for FSO is generally not subject to strict frequency-allocation and licensing requirements, although laser safety regulations and local restrictions may apply [1]. Challenges include misalignments of narrow beams, strong atmospheric attenuations through clouds and fog, and power fades caused by atmospheric turbulence. Atmospheric turbulence causes fluctuations of the received optical power. Deep fades of several milliseconds can cause link outages or reduce data rates. Consequently, mitigating deep fades is essential for link reliability and is the main objective of this work.

1.2 Exploitation of spatial diversity

Spatial diversity mitigates the impact of atmospheric turbulence by exploiting the reduced probability of simultaneous deep fades in spatially separated optical channels. The degree of correlation between the received signals depends on the spatial separation of the optical paths relative to the atmospheric coherence scale, commonly characterized by the Fried parameter [2]. Consequently, multiple spatially separated apertures can transmit or receive redundant replicas of the same data, and the individual received signals are subsequently combined to form a communication channel with improved reliability. When the separation between receiving apertures becomes larger than the relevant coherence scale, the received

power fluctuations become increasingly decorrelated, reducing the probability that all branches simultaneously experience a deep fade [2].

Combining is often performed in the digital domain, with the most common techniques being maximal-ratio combining (MRC), equal-gain combining (EGC), and selection combining (SC), which offer different trade-offs between performance and implementation complexity [3]. Selection combining provides a lower-complexity alternative where a performance metric (typically, the received optical power or signal-to-noise ratio) of each channel is monitored and the channel with the highest metric is selected for transmission.

Figure 1 compares the theoretical performances of the combining methods SC and EGC for different numbers N of diversity channels. Diversity channels are assumed to be independent and identically distributed. They follow a gamma distribution with two different fluctuation strengths represented by the squared coefficient of variation (SCV) taking values of 0.5 and 2 (blue and red curves, respectively). The SCV is the mean-normalized variance. Thus, if fluctuations are caused by scintillation, SCV is equivalent to the scintillation index [4]. The SCV does not affect the mean received power. The two graphs a) and b) of Figure 1 display the same cases but over different axis parameters: a) CDF (cumulative density function) vs. Rx power, b) Rx power vs. number N of diversity channels. Curves show that for a few diversity channels and strong fluctuations (SCV > 1), EGC and SC offer close diversity performance, i.e. fade reduction. However, as N increases, EGC outperforms SC because EGC has a higher array gain, i.e. mean-value increase.

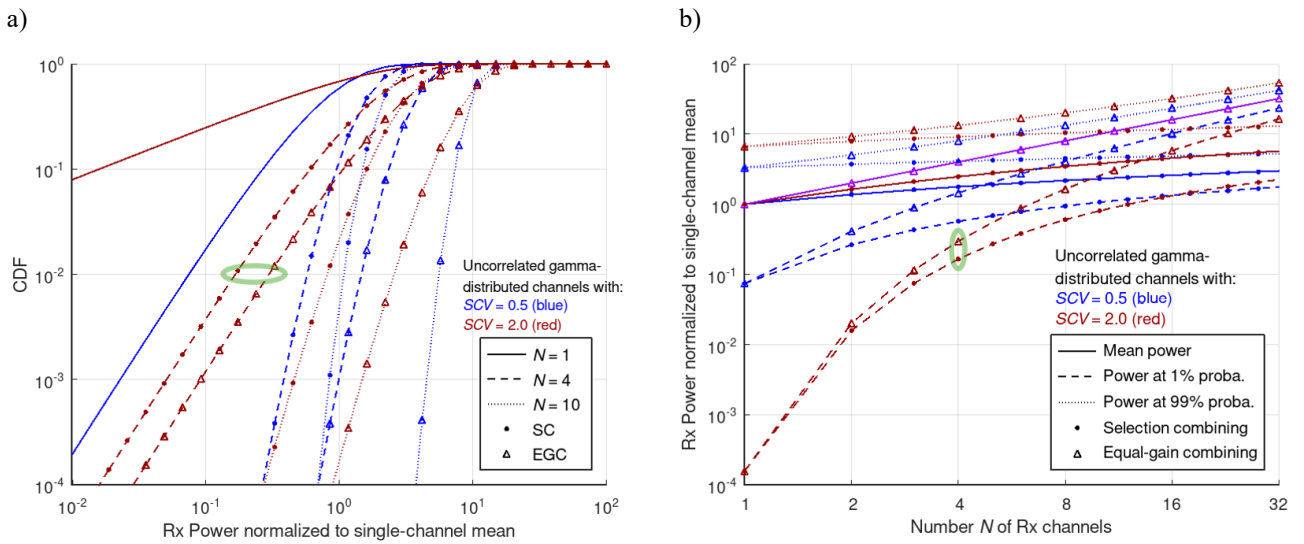


Figure 1: Theoretical performance of selection combining (SC) and equal-gain combining (EGC). a) Cumulative density function (CDF) of received powers. b): Received power versus number of uncorrelated Rx channels. SCV is the squared coefficient of variation (i.e. the mean-normalized variance). For each uncorrelated channel, a gamma distribution is assumed with an SCV of either 0.5 or 2. To simplify the comparison of the left and right graphs, two samples representing the same cases have been encircled in light green in both graphs: this is the optical power received after SC and EGC of 4 uncorrelated channels with SCV = 2, and below which fades take place with 1% probability.

Combining can be done in the (electrical) digital domain or in the optical domain. Digital combining requires an independent detection and processing chain for each optical path with additional digital processing, thereby increasing the hardware complexity. On the other hand, optical combining requires a single optoelectronic receiver. In the optical domain, selection combining can take the form of an electronically controlled ultrafast optical switch. To our best knowledge, optical selection combining for FSO fade reduction has not been demonstrated.

1.3 Reciprocity between up- and downlink

The physical selection of the best optical path enables fade mitigation in both transmission directions by exploiting the reciprocity principle [5]. Reciprocity implies that the channel attenuation (e.g. fade depth) is identical in both directions provided that the channel does not significantly change during the propagation time. For example, a 30-km free-space channel shall not significantly change over 100 μ s. For satellite links, the satellite speed creates a fast-changing propagation channel that decreases the level of reciprocity. Reciprocity also requires the same wavelength and polarization for both directions, or negligible wavelength- and polarization-dependent losses. The path common to both directions shall also be free of non-reciprocal components (e.g. optical circulators). The experimental setup described hereafter has been built with the goal of fulfilling the reciprocity conditions.

2 EXPERIMENTAL SETUP

2.1 Bidirectional 3-km link

The proposed concept of optical combining is deployed on 3.2 km FSO link, which has been used as spatial-diversity test range in previous experiments of the Heinrich-Hertz Institute (HHI) [6][7][8]. The link exploits once more 4 spatial diversity channels with a 4-telescope array, called multi-aperture terminal (MAT), on the main building of HHI and a single-aperture terminal (SAT) at a location provided by Deutsche Telekom (see Figure 3). For a refractive-index structure parameter of $C_n^2 > 5 \times 10^{-15} \text{ m}^{-2/3}$ representative of moderate-to-strong atmospheric turbulence, the Fried parameter is estimated to be below 0.1 m. Accordingly, the MAT apertures are placed at the corners of a square with a side length of 10 cm. This separation is chosen to provide sufficiently decorrelated optical paths and thereby enable effective exploitation of spatial diversity. All apertures of the setup are identical with an effective Gaussian radius of 20 mm.

The schematic of the experimental setup is shown in Figure 2, with the MAT on the left and the SAT terminal on the right. At the MAT, 10% of the received optical power from each aperture is monitored using high-speed power meters at a sampling rate of 15 kHz before the optical switch. The measured power levels are compared by a microcontroller, which selects the optical path with the highest received power. The remaining 90% of the optical power is directed through the switch to the MAT receiver.

All fibers are standard (non-polarization-maintaining) single-mode fibers. To enable bidirectional measurements, both MAT and SAT send and receive laser light with a circulator that duplexes the Rx and Tx channels and provides a common optical path over the FSO channel and the optical switch. Because, in this proof-of-concept, we are only measuring optical powers, both the MAT receiver and SAT receiver are actually powermeters.

The wavelength emitted by the MAT and SAT are respectively the C20 and C47 channels of the ITU DWDM grid around 1550 nm. The channels are intentionally separated in wavelength to reduce the noise floor at the receivers caused by back-reflections and the limited directivity of the optical circulators. The transmitted optical power is amplified using an erbium-doped fiber amplifier (EDFA) to 10 dBm on both terminals.

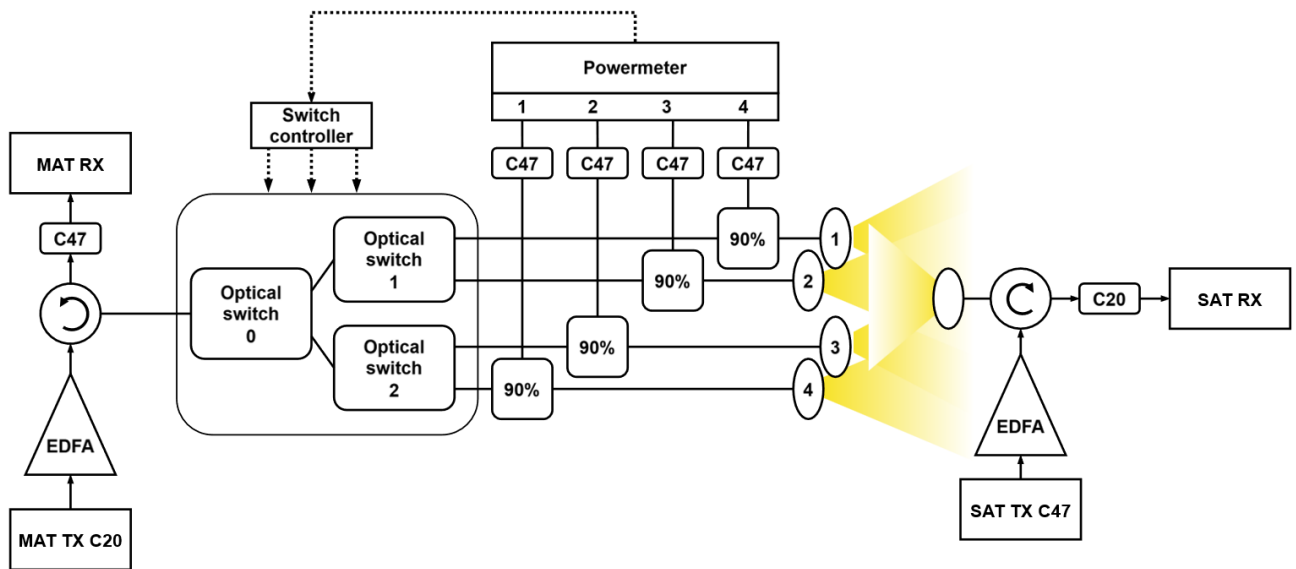


Figure 2. Setup diagram with: C20/C47 – DWDM 100GHz filters; EDFA – erbium-doped fiber amplifier, RX – receiver, TX – transmitter; MAT – multi-aperture terminal; SAT – single-aperture terminal; 90% – 10 dB coupler where 10% are used to control the optical switches and 90% goes through the switch to the RX.

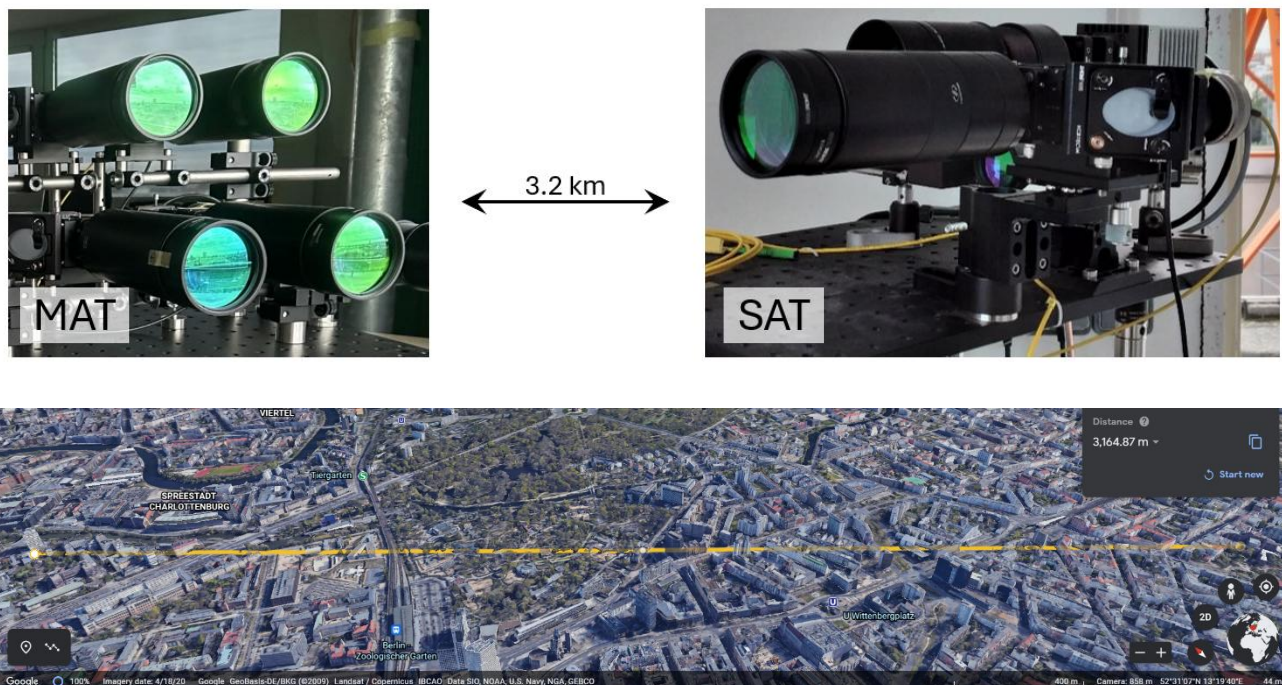


Figure 3: FSO test range in Berlin used for the experiment.

2.2 Optical switch

The deployed fiber-based 1x4 optical switch consists of three 1x2 optical switches, model NSSW-1251113311 from Agiltron ©. The main parameters of the used 1x2 optical switch are presented in Table 1:

Parameter	Value
Insertion loss	1.5 dB
Electrical-optical delay	250 ns
Response time (optical transition period)	$\sim 1\mu\text{s}$ (measured)
Max. repetition rate	100 kHz

Table 1: Parameters of the 1x2 optical switches.

The switch states are controlled by the applied electrical voltage. The electrical-optical delay of 250 ns is the time between the change of the electrical input signal and the start of the optical switching. During the optical-switching transition (or switch response time), the optical output of the switch is unreliable due to the wave interference occurring in the fiber. The electro-optical delay of 250 ns and the transition period of about $1\mu\text{s}$ are shown in Figure 4. An estimate of the data loss percentage is given by the product of the switching transition period and the average switching frequency. For example, operating the switch every millisecond will result in roughly 0.1% of transition time (and thus of potential data loss).

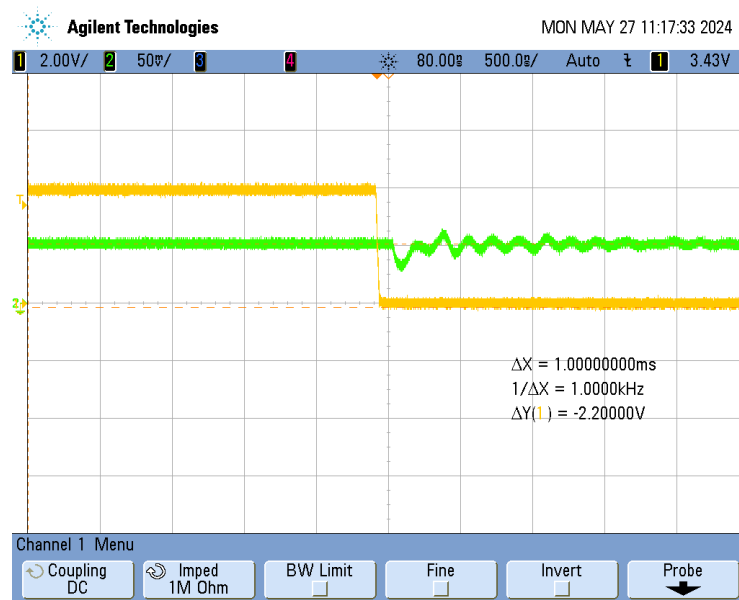


Figure 4: Interference of two optical waves after the switching. Orange - applied electrical voltage; green - measured optical power at the switch output.

The optical switch is controlled by a microcontroller located at the MAT, which simultaneously acquires the received-power measurements from the four spatial channels. These measurements are used in real time to make the selection-combining decision and are also recorded on a PC for post-processing analysis. The SAT Rx power is measured at the same sampling rate. Consequently, the measurements presented in §3 comprise six power-monitoring channels: four corresponding to the individual MAT apertures, one corresponding to the MAT receiver after optical combining, and one

to the received signal at the SAT side. All six measured power channels are collected and aggregated on a PC at the MAT side.

3 EXPERIMENTAL RESULTS

Figure 5 shows the cumulative distribution functions (CDF) of the received powers measured during 3 minutes on 2026-August-16 at 17:00. As expected, the CDFs of the 4 individual apertures exhibit deeper fades than the CDFs with selection combining at MAT and SAT. The curve "post-processed SC" refers to the numerical instantaneous maximum of the 4 powers measured from the individual MAT apertures. As this post-processing selection combining does not account for the approximately 3dB insertion loss of the optical switch, it serves as an ideal reference.

The difference in performance between optical combining at the MAT and SAT sides can be attributed to imperfect channel reciprocity. The measured correlation coefficient between uplink and downlink for each MAT aperture falls in the range of 0.85-0.97. No significant polarization-dependent loss was identified in the setup. However, the wavelength difference between the downlink C47 and the uplink C20 channels is about 22 nm. The measured partial reciprocity is likely related to wavelength-dependent losses in the optical paths. This assumption is to be consolidated by further investigations.

Table 2 lists the mean values and the squared coefficients of variation (SCV) of the received powers. The decrease of SCV after selection combining indicates the reduction of fluctuations.

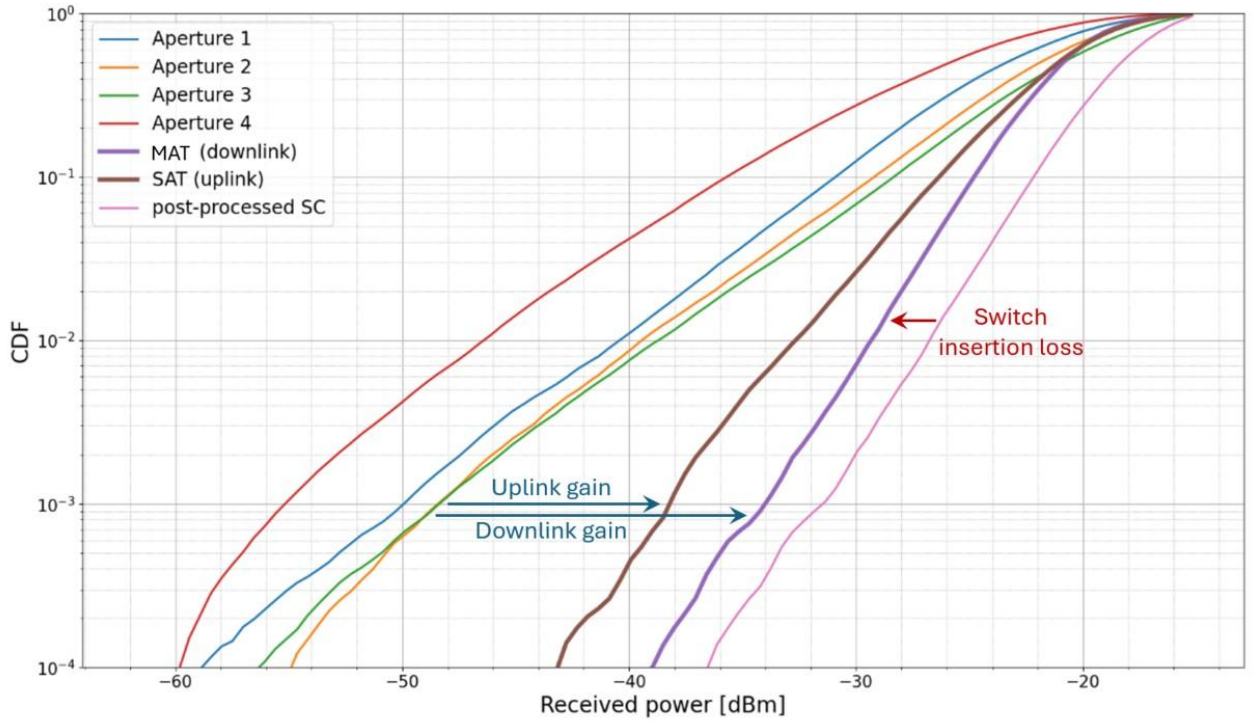


Figure 5: CDF of received powers for individual diversity channels (Aperture 1 to 4) and after optical combining (MAT and SAT).

Optical system	Mean received power [dBm]	Squared coefficient of variation (SCV)
Optical combining MAT	-20.38	0.451
Optical combining SAT	-20.40	0.596
Post-processing SC MAT	-17.40	0.462
Aperture 1, MAT	-21.57	1.304
Aperture 2, MAT	-20.50	0.948
Aperture 3, MAT	-19.14	1.007
Aperture 4, MAT	-23.26	1.592

Table 2: Statistics of Figure 5

4 CONSIDERATIONS FOR DATA TRANSMISSION

4.1 Delays and transitions

For optical combining, differences between optical path lengths must be compensated to the precision required by the signal bandwidth (i.e. data symbols from different diversity channels must arrive at the same time).

For optical selection combining, the impact of transitions between switching states shall be considered. During switching transitions, light from both branches may be coupled into the output fiber, potentially causing interference and signal distortion. With an average switching frequency f_{switch} and a switching transition time $T_{transition}$, the outage rate R_{outage} is given by:

$$R_{outage} \approx f_{switch} T_{transition}. \quad (1)$$

With $f_{switch} = 1$ kHz and $T_{transition} = 1$ μ s, the outage rate is about 0.1%. One approach to mitigate this drawback would be to implement custom DSP function with buffering at the transmitter to avoid the transition periods. Since switching is a controlled and predictable event, data transmission could be temporarily suspended during the switching transition. This possible mitigation could solve the path-length correction, as the buffering time could take into account the different delays associated with the different apertures.

4.2 Quantum key distribution (QKD)

QKD requires a physical optical channel to transmit quantum states between the communicating parties. This optical channel can be fiber or free space. Because the QKD quantum channel is less sensitive to the loss of symbols than classical communications, optical selection combining is well suited for QKD. In particular, an outage rate of 0.1% with transition periods of 1 μ s does not affect the QBER (quantum-bit error rate) significantly.

For the differences in the optical-path lengths, current QKD systems allow for fast re-synchronization recovery at approx. 7 ms/km which in our case for the differences in the range of several cm would result in re-synchronization time less than 0.5 μ s [9].

5 CONCLUSION

In a proof-of-concept experiment, we demonstrated the benefits of optical selection combining for a 3.2-km free-space optical link with significant scintillation. By utilizing a 4-telescope array and a fast optical switch, the proposed technique provides effective mitigation of deep fades, substantially reducing the probability of signal dropouts. The implemented optical combining counteracts turbulence-induced fades occurring on the millisecond time scale by dynamically selecting the optimal optical path.

Our bidirectional measurements revealed only partial channel reciprocity, with correlations between 85% and 97%. This partial reciprocity indicates a deviation from ideal bidirectional-channel behavior, likely influenced by wavelength-dependent losses as the up- and down-links use slightly different wavelengths.

The switching process inherently introduces short signal disruptions during the transition periods. These microsecond-scale disruptions are regarded acceptable for QKD applications, where their impact on the QBER remains minimal. In contrast, these switching transition impairments must be strictly avoided for high-speed classical communication, as they can cause signal distortion and data loss. Switching transitions can be avoided with relatively complex mitigation strategies like transmitter buffering.

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