

Ultrafast Indoor Optical Wireless Communications



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Well, to be honest this feels like a short journey. Life flies away faster than a sunny day in Britain (weather ‘joke’: check!). Three years and +100 pages after, I think I will continue doing research. And this PhD is perhaps a confirmation of my commitment to Science and Engineering...And before this turn into an ode-type discourse, let me focus on the purpose of this writing. I take a moment to acknowledge my colleagues, friends and family, in that order.

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ABSTRACT

Traffic from wireless and mobile devices is predicted to increase 10-fold between 2014 and 2019, surpassing wired data traffic by 2016. Given the expected radio frequency (RF) capacity crunch, this growing wireless demand will have to be met using a variety of new technologies exploiting other parts of the electromagnetic spectrum. Promising research areas include the Millimetre Band as well as Optical Wireless Communications (OWC).

Millimetre Band demonstrations have accomplished ultrafast multi-Gigabit links, making use of state-of-the-art fibre transmission systems. However, complex opto-electronic (OE) interfaces are required to convert the optical carrier into Millimetre wireless signals. To avoid these interfaces, an all-optical transparent network is proposed here, spanning over both the fibre and OWC domains, in order to deliver ultrahigh data rates to mobile end-users in indoor environments. This is supported by the recent deployment of fibre-to-the-home (FTTH) networks creating the potential for Terabit aggregate connections at the user's doorstep.

Therefore, infrared fibre-wireless-fibre (FWF) links are studied to support data rates over 100 Gb/s in nomadic applications. The link coverage is achieved via narrow beam beamsteering over a wide field-of-view (FOV) using suitable localization and tracking techniques. The proposed model is inherently bidirectional and transparent, i.e. independent of the data rate and modulation format.

In this thesis, the potential for ultrafast wide coverage OWCs using SMF-based transceivers and coherent transmission is demonstrated. A record data rate of 418 Gb/s and 209 Gb/s with a wide FOV of $\theta_{FOV} = \pm 30^\circ$ and $\theta_{FOV} = \pm 20^\circ$, respectively, is shown at a free space range of 3 m. To the best of our knowledge, this is the fastest demonstration of an indoor wireless link that offers

practical room-scale coverage. The automated alignment of this FWF link is also demonstrated with the design and implementation a mm-accurate localization and tracking system. Finally, architectures for point-to-multipoint communications are explored in order to adapt the system to multiple users.

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Chapter 1

Introduction

1.1 MOTIVATION

Societies are experiencing a data traffic growth driven by an explosion of volume of information, number of devices and transactions [1]. It is predicted that traffic from wireless and mobile devices will increase 10-fold between 2014 and 2019, surpassing wired data traffic by 2016 [2]. At the same time, the electromagnetic spectrum below 6 GHz is being exhausted [3]. This so-called radio frequency (RF) capacity crunch has led to communications research exploiting unlicensed bandwidths at higher frequencies in the electromagnetic spectrum. Promising technologies include the Millimetre wave-band as well as Optical Wireless Communications (OWC) [4]–[9].

The mm-waveband extends from 30 to 300 GHz [5]. The name is given because the wavelengths for these frequencies vary between ~ 1 -10 mm. Although parts of this band are already reserved for satellite or other well regulated applications, there are available regions in the E (60 -90 GHz) and W (75-110 GHz) sub-bands suitable for short range data communications [10],[11]. By using beam-forming and multiple-input multiple-output (MIMO) techniques, Millimetre-wave technology is being considered for the next generation 5G cellular communications [12], [13]. Demonstrations of ultrafast data rates of 400 Gb/s [14] and 100 Gb/s [6] have been reported at a link range of ~ 1 m and 20 m, respectively, using state-of-the-art optical fibre-based transmission systems. However, complex opto-electronic (OE) interfaces are required to convert the optical carrier into an mm wave. Moreover, bulky beam forming antennae are required for >100 Gb/s data rate links limiting the system's mobile (even nomadic) capabilities. Lower data rates have also been studied with Radio-over-fibre (RoF) and radio-and-fibre (R&F) techniques, that have the

potential to enable low cost implementations [15], but are limited by available bandwidth and regulation [9], [16].

On the contrary, using light from an optical fibre to create OWC links is attractive [17], as it offers $\sim$ THz unlicensed bandwidth, robustness against interference and secured transmissions confined to the room where the communication originates [18]. There are two spectral regions of interest: visible light (400-700 nm) and infrared wireless (700 – 1700 nm). Visible light communications (VLC) has gathered momentum in recent years by making use of the existing illumination infrastructure to also deliver information [8], [19], [20]. It has also been proposed for future 5G communication networks [21]. However, to date the experimental demonstrations have achieved data rates at least an order of magnitude lower than that achieved using Millimetre-wave approaches. Moreover, VLC compatibility with optical (infrared) fibre networks is limited due to different wavelengths of operation.

In this work, infrared wireless communications is investigated to achieve ultra-high data rates higher than 100 Gb/s. Specifically, the telecommunications C-band ($\sim$ 1550 nm) is considered given its widespread use in fibre communications. The potential to create an all-optical network, spanning over both wireless and fibre domains, is shown. The scope is focused on to indoor environments, motivated by the recent growth in fibre-to-the-home (FTTH) deployments.

1.2 ULTRAFast OPTICAL FIBRE-WIRELESS COMMUNICATIONS

Fibre-to-the-home (FTTH) is projected to become the dominant broadband access technique worldwide over the next 2 decades [22]. Complex modulation techniques and dense wavelength division multiplexing (DWDM) are expected to be used in these networks [23], [24], along with the standardization of 100 Gigabit Ethernet (GbE) [25]. The associated implementation using the

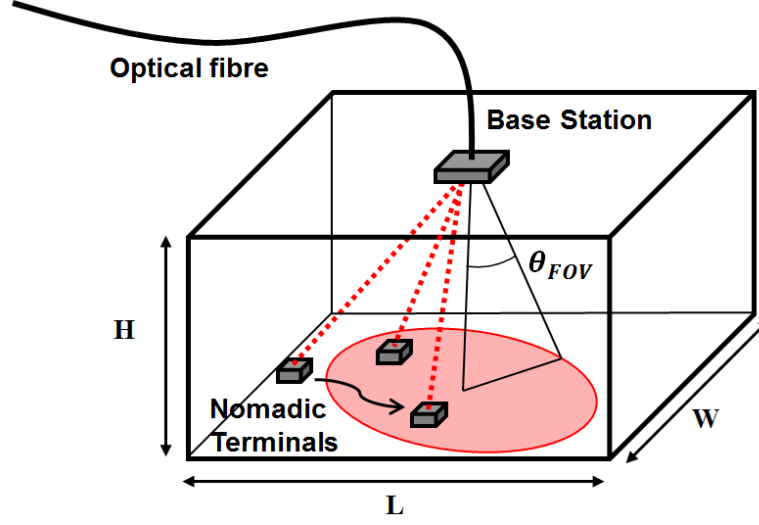


Figure 1. Wireless access to a fibre backbone: indoor application. The room has dimensions of $L \times W \times H = 4 \text{ m} \times 4 \text{ m} \times 3 \text{ m}$. The red dotted lines are wireless communications links. The shaded area is the base of a cone with half-angle θ_{FOV} .

next generation of passive optical networks (NG-PONs) will potentially deliver Terabit/s aggregate capacities to indoor environments within metropolitan areas [26],[27].

Ideally, mobile users would connect to this infrastructure using wireless systems operating at data rates matching those on the fibre network. A potential scenario is shown in Figure 1. A static base station (BS) on the ceiling is connected to an optical fibre network, such as an NG-PON, which is installed as part of an in-building infrastructure. The BS then communicates via ultrafast OWC links with nomadic terminals (NTs) within the room.

For such OWC links, Class 1 laser safety regulations limits the emission power to 10 dBm at 1550 nm [27], [28]. At the same time, ultrafast links require sufficient optical power at the receiver to maintain good bit error rate (BER) performance. As a consequence, these links are designed to be narrow beams that maximize the signal strength at the NT receivers [29]. The challenge is considerable though in indoor applications where the BS has to provide a realistic coverage area,

e.g. an area $L \times W = 4\text{ m} \times 4\text{ m}$ at a range $H = 3\text{ m}$ as shown in Figure 1. A routing system with the following functions is then required: (1) beamsteering of the infrared narrow beams over a practical field of view (FOV), e.g. $\theta_{FOV} \geq 20^\circ$ (half-cone angle); (2) a localization and tracking system to point and follow the NT movement within the coverage area; and (3) point-to-multipoint capabilities to distribute the available data capacity over different users.

The BS architecture and functionality requirements have been outlined thus far. However, the NT design has not been defined yet. To accomplish this, the next section first reviews the state-of-the-art of narrow beam OWC. Based on this review, a link architecture suitable for ultrafast transmission systems is proposed involving both the BS and NT transceivers. Then, the research challenges and aim of this thesis are outlined.

1.3 SYSTEM ARCHITECTURE

Ultrafast indoor OWC demonstrations have been reported over fibre-wireless-fibre (FWF) link geometries [30], [31]. FWF laboratory experiments have achieved Terabit/s data rates using orbital angular momentum (OAM) multiplexing techniques and coherent transmission [32], [33]. Single-mode fibre (SMF) transceivers have typically been used, although multi-mode fibre (MMF) realizations have also been successful [34]. The advantages of a FWF design are:

1. Link transparency: no electro-optical interfaces through the wireless architecture, i.e. the architecture is independent of the data rate and modulation formats used by the transceivers.
2. Compatibility with fibre networks: All-optical networks are possible at the wavelength of operation (typically $\sim 1550\text{ nm}$), which also allows the use of C-band off-the-shelf components.

3. Link bi-directionality: Due to the reversibility of light, if the downlink is aligned then the uplink is automatically aligned. This is particularly relevant for narrow beam communications, where the free space link is highly directional.

Therefore, an FWF link architecture is chosen where both the BS and NT are designed as SMF-based transceivers. The challenge is to achieve practical coverage whilst maintaining high data rates. In recent ultrafast FWF demonstrations, fixed co-aligned transceivers have been used resulting in negligible coverage area as shown in Figure 2 (these are shown as points on the y axis, where the coverage area is $\sim$ zero). Some research efforts have focused on enhancing the coverage area (Figure 2, points outlined in red). Wang et al. [9] achieved a 4 x 12.5 Gb/s link with a relatively large coverage area of $>3 \text{ m}^2$; but the demonstration was not bi-directional and the

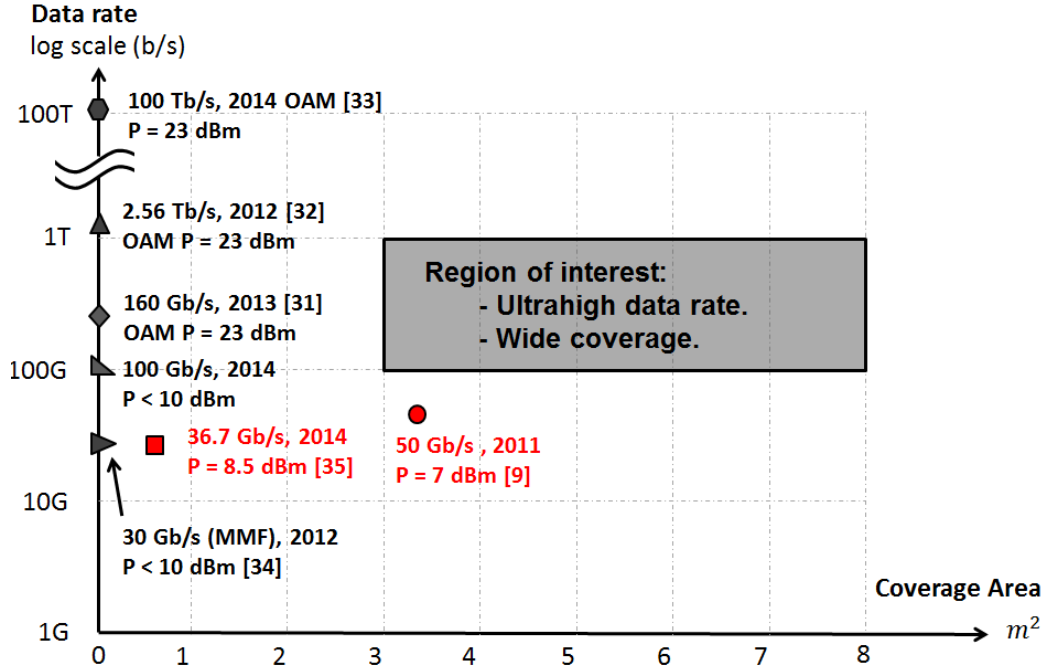


Figure 2. Demonstrations of ultrafast infrared FWF links. The data rate is plotted as a function of the coverage area. The experiments in red used intensity-modulation direct-detection and those in black coherent detection. P is the transmitted power and OAM is orbital angular momentum.

receiver needed to be normally oriented to the incoming beam direction. Koonen et al. [35] also designed a FWF link with a high data rate of ~ 37 Gb/s. However, the coverage area was below 1 m^2 and, again, the receiver had to be aligned normally to the incoming beam.

These demonstrations suggest that there is a trade-off between the link's data rate and achievable coverage. This thesis will study this trade-off focusing on the shaded region of interest shown in Figure 2. The aim is to design and demonstrate of a fully functional link with practical coverage and data rates over 100 Gb/s. Figure 3 shows the proposed FWF link architecture. A transmitter (Tx) is connected via an SMF fibre to a beamsteering unit. A narrow beam is generated with a given direction $\theta_l < \theta_{FOV}$ and a maximum output power of $P_{Tx} = 10$ dBm. The beam then propagates through free space until it reaches a second beamsteering unit at the receiver (Rx) end. The light is steered back into an SMF fibre to be processed by the Rx.

The Tx / Rx choice is independent of the wireless link and beamsteering units, given the transparency property of FWF architectures. Still, in Figure 2 all demonstrations with data rates above 100 Gb/s are based on coherent transmission. Therefore, a coherent system is a good candidate to test the data rate limits of the proposed FWF link.

Having SMF fibres at both ends of the link, creates great challenges. A careful alignment needs to be carried out at the transceivers to achieve efficient coupling into the fibre. Thus, the beamsteering units are modules where high steering accuracy is required as well as a large steering range. The automation of the beamsteering and alignment process is an additional degree of complexity that is also studied in this thesis. Finally, the generalization from a single link to multiple beams to have a point-to-multipoint implementation will be considered. The next section expands on these ideas by defining the thesis structure.

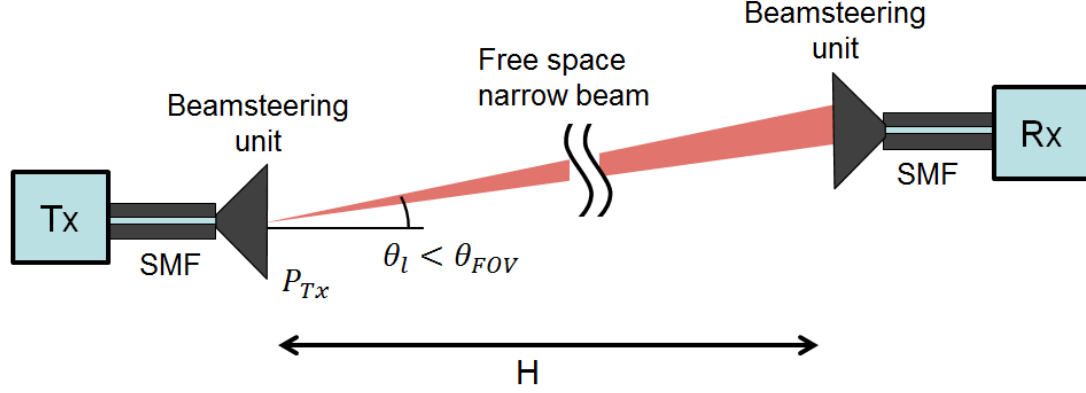


Figure 3. Fibre-wireless-fibre (FWF) link design. P_{Tx} is the beam output power just after the transmitter. θ_l and θ_{FOV} are the link angle and maximum link angle, respectively.

1.4 THESIS OUTLINE

The thesis outline is as follows:

- **Chapter 2: Optical beamsteering.** Beamsteering techniques are studied to support ultrafast OWC with SMF fibre-based transceivers. Emphasis is made on non-mechanical holographic beamsteering using spatial light modulators (SLMs). Passive angle magnification is introduced to enhance the active beamsteering FOV.
- **Chapter 3: Single link communications.** An indoor wireless link is designed and implemented using FWF geometry. A record data rate of 200 Gb/s is achieved for a wide angle FOV $> \pm 30^\circ$ at a range of ~ 3 m (~ 3 m x 3 m coverage area). The potential for Terabit data rates is demonstrated.
- **Chapter 4: Localization and tracking systems.** A fully integrated and automated localization and tracking system was designed and experimentally characterized for the FWF link given in Chapter 3. Localization accuracies of 2.5 mm were achieved at a range

of 3 m (measured angle of arrival precision of 0.05°). The system is suitable for nomadic applications with a tracking response of seconds.

- **Chapter 5: Point-to-multipoint communications.** Chapter 5 explores architectures to achieve point-to-multipoint downlink communications. This study addresses the problem of distributing wavelength channels of a WDM comb amongst several nomadic terminals. The SLM point-to-multipoint capabilities are demonstrated using the principles of division of aperture and division of wavefront.

1.5 KEY CONTRIBUTIONS AND LIST OF PUBLICATIONS

The key contributions of this research are:

- Design and demonstration of ultrafast fibre-wireless-fibre links with data rates higher than 200 Gb/s and wide field-of-view of $\pm 30^\circ$. Indoor coverage was achieved by using narrow beam beamsteering. The trade-off between link coverage and data rate was modelled.
- Design and demonstration of an automated localization and tracking system suitable for narrow beam indoor optical wireless communications. A localization accuracy of 0.05° was achieved using angle of arrival measurement techniques.
- Design and experimental study of point-to-multipoint indoor optical wireless communications using spatial light modulators and wavelength division multiplexed beams. Narrow beam beamsteering in combination with division of wavefront and division of aperture principles were used to develop a proof-of-principle based on two-beam beamsteering.

From these contributions and other collaborations, original work published over the course of this research (from October 2012 to May 2016) is listed below:

1. **A. Gomez**, Kai Shi, C. Quintana, Masaki Sato, G. Faulkner, B. Thomsen, and D.C. O'Brien, "Beyond 100Gb/s indoor Wide Field-of-View Optical Wireless Communications", IEEE Photonics Technology Letters, Vol 27, Issue 4, January 2015. ISSN 1041-1135
2. **A. Gomez**, Kai Shi, C. Quintana, G. Faulkner, B. Thomsen, and D.C. O'Brien, "A 50 Gb/s Transparent Indoor Optical Wireless Communications Link With an Integrated Localization and Tracking System", IEEE Journal of Lightwave Technology, Vol 34, Issue 10, March 2016. ISSN 0733-8724
3. **A. Gomez**, Kai Shi, C. Quintana, Robert Maher, G. Faulkner, Polina Bayvel, B. Thomsen, and D.C. O'Brien, "Design and Demonstration of a 400 Gb/s Indoor Optical Wireless Communications Link", IEEE Journal of Lightwave Technology (submitted), May 2016
4. **A. Gomez**, C. Quintana, G. Faulkner, and and D.C. O'Brien, "Point-to-multipoint holographic beamsteering techniques for indoor optical wireless communications", SPIE Photonics West, February 2016. DOI:10.1117/12.2213252
5. **A. Gomez**, C. Quintana, G. Faulkner, and and D.C. O'Brien, "Challenges in Wide Coverage Indoor Optical Communications Using Fibre-Wireless-Fibre Links for Terabit data rates", IEEE Global Communications Conference, December 2015. DOI: 10.1109/GLOCOMW.2015.7414094
6. **A. Gomez**, C. Quintana, G. Faulkner, and D.C. O'Brien, "Towards terabit wide coverage indoor optical wireless communications," Royal Society Meeting on 'Communication networks beyond the capacity crunch', May 2015.

7. **A. Gomez**, G. Faulkner, and D.C. O'Brien, "Infrared beamsteering with photorefractive materials", International conference on photorefractive effects, materials and devices (poster presentation) , Winchester (UK), Sept 2013.
8. K. Shi, **A. Gomez**, X. Jin, Y. Jung, C. Quintana, D. O'Brien, F. P. Payne, P. Barua, J. Sahu, Q. Kang, S. Alam, D. J. Richardson and B. C. Thomsen, "Simplified Impulse Response Characterization for Mode Division Multiplexed Systems," in Optical Fibre Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2016). DOI:10.1364/OFC.2016.W4F.3.
9. X.Q. Jin, **A. Gomez**, D.C. O'Brien, and F.P. Payne, "Influence of Refractive Index Profile of Ring-Core Fibres for Space Division Multiplexing Systems", IEEE Xplore (2014 Society Summer Topicals Meeting Series), July 2014. DOI: 10.1109/SUM.2014.98
10. X.Q. Jin, **A. Gomez**, Kai Shi, Benn C. Thomsen, Feng Feng, George S. D. Gordon, Timothy D. Wilkinson, Y. Jung, Q. Kang, P. Barua, J. K. Sahu, S. Alam, D. J. Richardson, D.C. O'Brien, and F.P. Payne, "Mode Coupling Effects in Ring-Core Fibres for Space-Division Multiplexing Systems", IEEE Journal of Lightwave Technology (Accepted), April 2016.
11. Quintana, **A. Gomez**, G. Erry, G. Faulkner, Y. Thueux, D. O'Brien, "Novel non-mechanical fine tracking module for retroreflective free space optics", SPIE Security and Defense, September 2014. DOI:10.1117/12.2070225

Chapter 2

Optical beamsteering

2.1 OVERVIEW

In the introduction a fibre-wireless-fibre (FWF) architecture is proposed to achieve an ultra-high data rate indoor OWC link. Wide room coverage is targeted to satisfy practical wireless applications in indoor environments. Within the coverage area, the fibre-based transceivers require accurate beamsteering (to within fractions of a degree [36]) for power coupling optimization, particularly using SMF fibres.

In this chapter, the beamsteering requirements for an SMF fibre-pigtailed receiver are first reviewed. Subsequently, optical beamsteering techniques are investigated. A survey is carried out for mechanical beamsteering, electrowetting techniques, photorefractive and dynamic holographic beamsteering. An SLM is chosen based not only on practical constraints such as availability but also on the potential to perform more complex functions such as correction for geometrical optical aberrations. A commercial SLM with a relatively small steering capability of a few degrees is then characterized. To enhance its beamsteering range, a passive angle magnification module is proposed. Finally, the adaptive optics capabilities of SLM are introduced.

2.2 BEAMSTEERING REQUIREMENTS FOR SMF-BASED RECEIVERS

Optical coupling into SMF fibres is a challenging task. The core diameter is typically of the order $10\text{ }\mu\text{m}$, and roughly the angle of acceptance α is given by its numerical aperture ($NA = \sin(\alpha) \sim 0.14 \rightarrow \alpha \sim 6^\circ$) [37]. Moreover, SMF fibres require mode matching, i.e. the optimal coupling efficiency is given when the incident wavefront converging towards the receiving fibre

U_{IN} matches that of the guided fundamental mode U_{SMF} in both amplitude and phase in the fibre facet plane [38]. The coupling efficiency η can be mathematically formulated using the overlap integral,

$$\eta = \frac{\left| \iint_{\mathcal{M}} U_{SMF}(x, y) U_{IN}^*(x, y) dx dy \right|^2}{\iint_{\mathcal{M}} |U_{SMF}(x, y)|^2 dx dy \iint_{\mathcal{M}} |U_{IN}(x, y)|^2 dx dy} \quad (1)$$

Where $\mathcal{M}$ is the area of integration in the fibre facet plane. For conventional SMF fibres at 1550 nm, the fundamental mode U_{SMF} can be approximated to a Gaussian profile with a mode field diameter of $\sim 10 \mu m$ [39].

For an optical wireless system, coupling of a free space beam into an SMF fibre requires a field transformation such that U_{IN} matches this relatively small Gaussian profile. Fibre collimator lenses are widely used to perform this task [38]. Amongst them, Graded index (GRIN) [40], ball [41] and tailored micro lenses [42] are highly efficient couplers. However, some form of beamsteering is needed to align the free space incoming beam to the collimator and fibre axis. Figure 4 shows the proposed architecture. An IR narrow beam is incident on the aperture of the receiver at an angle $\theta_l < \theta_{FOV}$, where θ_{FOV} is the targeted system FOV. A beamsteering module then steers the beam in the direction of the fibre optical axis creating an angle $\varphi_{foa} \ll \theta_{FOV}$ (ideally $\varphi_{foa} = 0^\circ$). Finally, the fibre collimator focuses the light onto the fibre facet. This design requires an accurate alignment, e.g. for GRIN lenses the beamsteering accuracy is $\varphi_{foa} < 0.2^\circ$ to keep the coupling loss below 10 dB [36].

Besides the beamsteering requirements, distortions of the IR beam wavefront in free space and through the optics & beamsteering module can induce additional coupling losses [43]. Therefore, it is desirable to have adaptive optics capabilities before the fibre collimator to compensate for

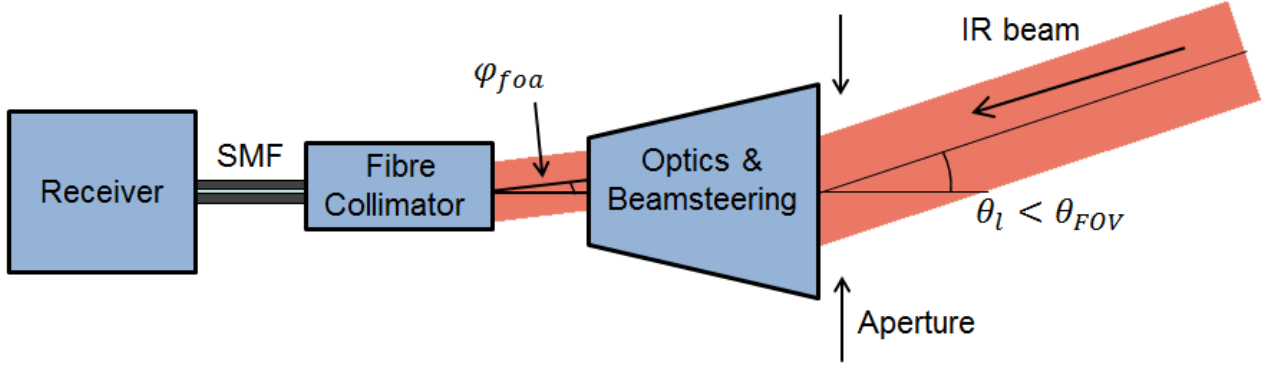


Figure 4. SMF fibre-pigtailed transceiver. φ_{foa} defines the angle the IR beam makes with the fibre optical axis after the optics & beamsteering module.

these expected aberrations as a function of the incident angle θ_l . This will be discussed later in the chapter once the beamsteering approach is determined. The next section gives a survey on beamsteering techniques suitable for the proposed IR receiver system.

2.3 BEAMSTEERING TECHNIQUES

Beamsteering devices are chosen based on their efficiency, steering accuracy, steering range (α), effective steering aperture (ω), and angle-switching speed. For the proposed FWF architecture, the angle-switching speed is not critical as this research targets nomadic (rather than mobile) applications. The remaining parameters are essential.

The product of the area $A(\omega)$ and solid angle $\Omega(\alpha)$ defines the beamsteering device's etendue, which is constant throughout the optical system [44]. The higher the etendue, the better the beamsteering device is (this will be shown in Chapter 3). Therefore, a high etendue $A(\omega) \cdot \Omega(\alpha)$ device is desired. An accurate beamsteering device is a requirement due to the fibre-based transceivers' design as discussed in section 2.2. Finally, the steering efficiency is also a key factor, given the need to limit transmitted power for eye-safety.

Based on the previous beamsteering requirements, Figure 5 shows a summary of potential beamsteering techniques for OWC. The following list gives an overview of each technique outlining the pros and cons:

1. **Mechanical steering mirror:** Feasible and straightforward solution for beamsteering of relatively small coverage (Figure 5 (a)) [45]. However, it has no adaptive optics capabilities. This aspect is important in the coupling efficiency and beam-forming

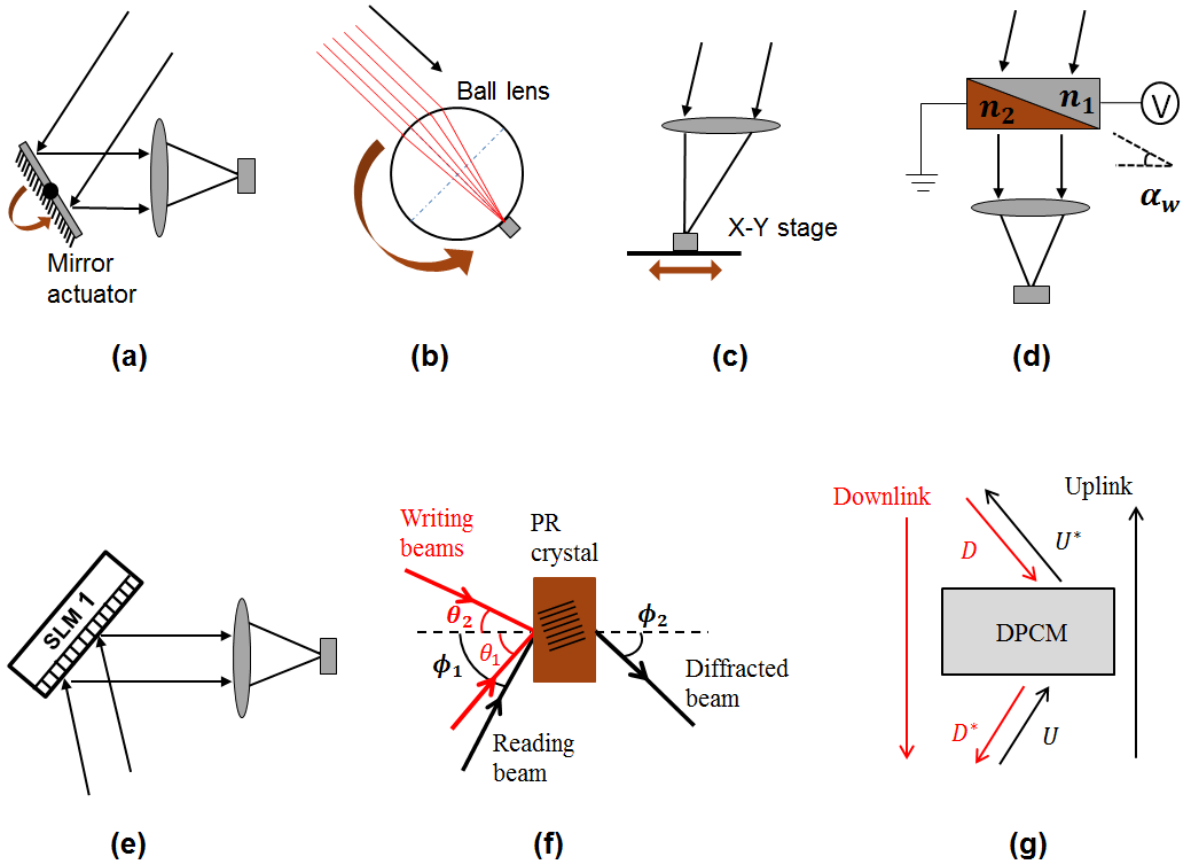


Figure 5. Beamsteering techniques: (a) mirror actuator steering, (d) ball lens rotator (c) 2D scanning table, (d) electrowetting with two liquids with different refractive indexes n_1 and n_2 , (e) SLM-based beamsteering (f) Two lambda method photorefractive beamsteering, and (g) Double phase conjugate mirror (DPCM) beamsteering.

using SMF-based transceiver as will be shown in the next chapter.

2. **Rotating ball lens:** A ball lens couples light to a detector which is fixed to it, and the ball can be rotated to align the detector in the correct direction (Figure 5 (b)). This method is attractive due to the good coupling efficiencies reported when focusing light into an SMF fibre [41]. However, it requires the design of a mechanical system to rotate the ball lens in a controlled manner.
3. **2D scanning table beamsteering:** A single focusing lens and a detector on an XY scanning table (Figure 5 (c)). In this configuration, the 2D scanning process is carried out in the rear focal plane of the collection lens. That is, the detector is translated to the position of the focusing beam to compensate for the beam walk as a function of the incoming beam direction. This method has been successful using a small area free space photo-detector [46]. However, its compatibility with a fibre-like receiver is limited as the fibre-optical axis is not aligned to that of the focusing optical lens.
4. **Electrowetting beamsteering:** This technique uses refractive wedges to create a beamsteering device (Figure 5 (d)) [47], [48]. The wedge angle between two liquids with refractive indexes n_1 and n_2 is controlled via an applied DC or AC voltage of the order of 10s of volts. The refractive index contrast $\kappa = n_1/n_2, n_1 > n_2$ determines the bending power of the device. Increasing κ proves challenging: to fabricate a robust electrowetting device (shielded against vibrations and gravity) the two contrasting liquids must have equal densities. Unfortunately, commercial devices were not available at the time this work was carried out, so this was not pursued.

5. **Spatial light modulator (SLM) beamsteering:** SLMs are arrayed devices that can spatially modulate the amplitude and phase of an incoming wavefront. Their pixelated nature allows for the generation of programmable diffraction patterns capable of accurate and efficient beamsteering (Figure 5 (e)) [49]. Amongst them, liquid crystal SLMs are a mature technology [50]–[52] and steering efficiencies higher than 80% and angle accuracy of the order of tens of arc-seconds have already been achieved [53]. SLM-based systems can also be used for adaptive optics [54]–[56], which is advantageous when coupling light into fibre-pigtailed receivers as discussed before in section 2.2.
6. **The 2-lambda method:** This uses a short wavelength pair of beams to write a grating in a photorefractive (PR) crystal which can then be used to steer the reading beam (Figure 5 (f)). Visible writing lasers and infrared reading beams can be used to create a programmable grating. To have good diffraction efficiencies, the Bragg matching condition needs to be satisfied between the reading beam and the holographic grating.
7. **Double Phase Conjugate Mirror (DPCM):** The principle is shown in Figure 5 (g). As opposed to the two-lambda method, only two beams are required. Input beams D and U are initially incident on a PR crystal. They exchange their spatial structures via phase conjugation whilst still carrying the original temporal information (intensity and average phase). A self-aligned bidirectional link is then established: the optical beams pairs (D, D^*) and (U, U^*) define the downlink and uplink optical paths as shown in Figure 5 (g). Due to the phase conjugation property, both links are strictly corrected for aberrations. This is well-suited for fibre-like NT transceivers where light can propagate

in both directions in the fibre connection. Beamsteering related applications were proposed in the late 1980's [57]. The major challenge with this approach is the availability of materials that can operate in the 1550nm fibre communications wavelength regime. At present there are no reported demonstrations at this wavelength.

2.4 FEASIBILITY STUDY

Based on the summary given in section 2.3, it is difficult to make a final decision as to what beamsteering technique approach is the optimal based on performance and cost. However, the DPCM approach potentially allows attractive properties such as link self-alignment and aberration-free beams. PR crystals are known to create the DPCM effect but at lower wavelengths than 1550 nm.

In order to investigate the potential and difficulties of the DPCM approach, a short experimental study was undertaken using PR crystals. The 2-lambda method was initially investigated as it allows for 1550 nm infrared beamsteering by means of visible writing beams.

2.4.1 2-lambda method

PR-based beamsteering techniques rely on the generation of optically induced phase gratings in bulk crystals [58]. These materials present their peak holographic efficiencies in the visible spectrum, dropping their performances to negligible values at 1550 nm [59]. The 2-lambda method uses a short wavelength pair of beams to write a grating in the PR crystal which can then be used to steer the 1550 nm communications beam. The writing beams require sufficient power (a few mWs each) as well as mutual temporal coherence in order to generate a strong grating.

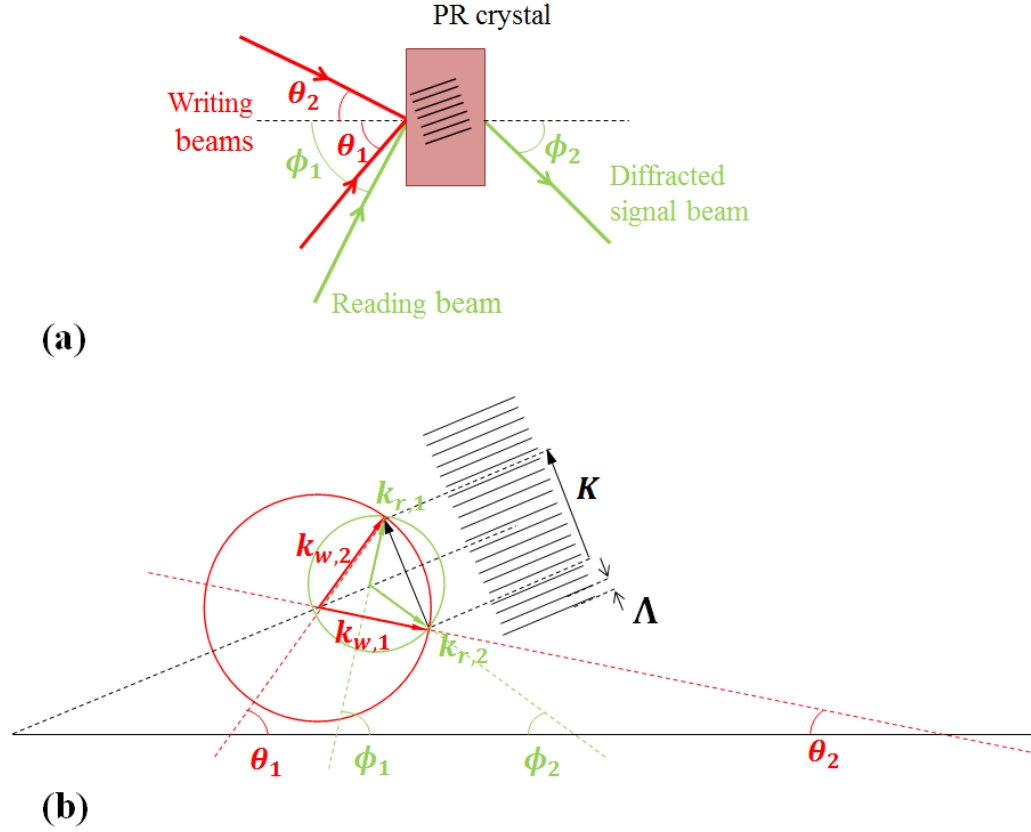


Figure 6. 2-lambda method (a) schematic (b) Bragg matching condition geometrical sketch in the k-space.

Figure 11 shows the principle of operation. The writing (visible) beams build up a PR grating and the reading (infrared) beam is diffracted by this grating structure. For optimal diffraction efficiencies, the Bragg matching condition needs to be satisfied between the reading beam and the grating. A grating wave vector $\mathbf{K}$ with magnitude $|\mathbf{K}| = 2\pi/\Lambda = |\mathbf{k}_{w,1} - \mathbf{k}_{w,2}|$ defines the hologram phase grating direction and pitch Λ as shown in Figure 6 (b). It can be shown using trigonometry the following conditions must be met:

$$\frac{\lambda_w}{\sin \frac{\theta_1 + \theta_2}{2}} = \frac{\lambda_r}{\sin \frac{\phi_1 + \phi_2}{2}} \quad \theta_1 - \theta_2 = \phi_1 - \phi_2 \quad (2)$$

Equation (2) limits the practical extent of a dynamic beamsteering system using the two-lambda method. That is, the efficiency of the diffracted reading beam is substantially reduced if the phase matching condition is not satisfied. Additionally, for dynamic infrared beamsteering an independent beamsteering device is required to control at least one of the writing beams.

2.4.2 Feasibility experiment

The performance of PR crystals was tested using a free space infrared communications link. The experimental setup is shown in Figure 7. A writing He-Ne laser (633 nm) is divided in amplitude

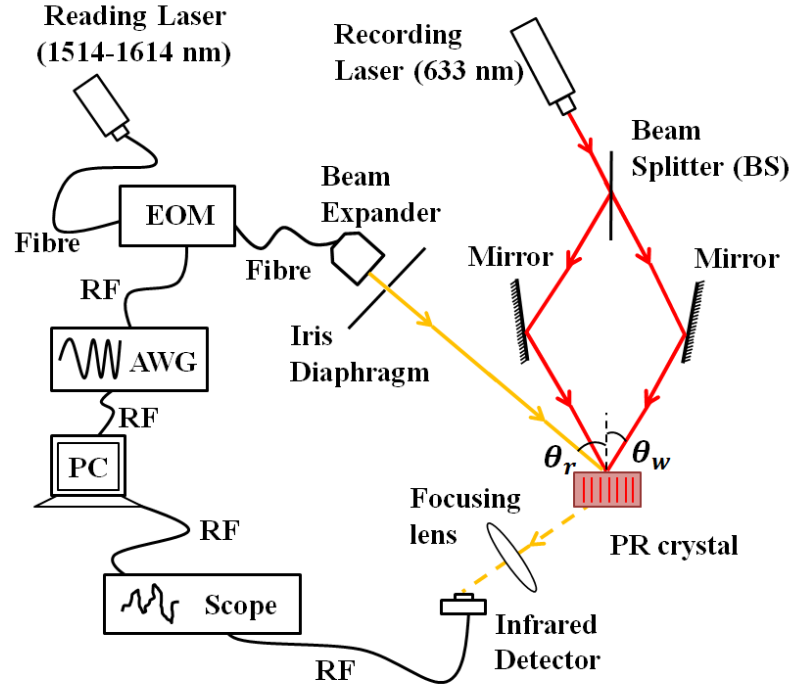


Figure 7. Experimental setup. The PR crystal is LiNbO₃ whose c axis is perpendicular to the grating lines. EOM is an electro-optical modulator (Corning waveguide modulator), AWG is an arbitrary wave generator (Agilent N8241A) and PC is a personal computer. The oscilloscope is an Agilent MSO7104B. The infrared detector is a balanced free space New Focus 1617 photoreceiver.

using a 50/50 pellicle beamsplitter. The resulting two beams are projected onto a LiNbO3 crystal (LiNbO3 was chosen due to availability at the time of the experiment) so that they interfere within the sample. The writing angle $\theta_w \sim 16^\circ$ is chosen using equation (2) so that a theoretical $\theta_r \sim 43.5^\circ$ fulfils the Bragg-matching condition when $\lambda_r = 1550$ nm.

An InGaAs camera was initially used to align the infrared beam in order to find a good diffraction spot image. A diffraction efficiency measurement as a function of the reading wavelength was then carried out. For this, the infrared camera was substituted by a free space detector (Newport 1617 InGaAs, 800 MHz bandwidth). The results are shown in Figure 8. The diffraction efficiency is dependent on the reading wavelength λ_r . An efficiency peak of $\sim 13\%$ (comparable to those reported in [59]) is obtained for $\lambda_r = 1553.5$ nm. Efficiencies above 1% occur for a 10 nm span centred at ~ 1553.5 nm. The peak efficiency deviation from the expected 1550 nm wavelength can be explained due to angular misalignments in the setup.

Finally, an error-free 625Mbps infrared optical link was achieved using the infrared reading beam

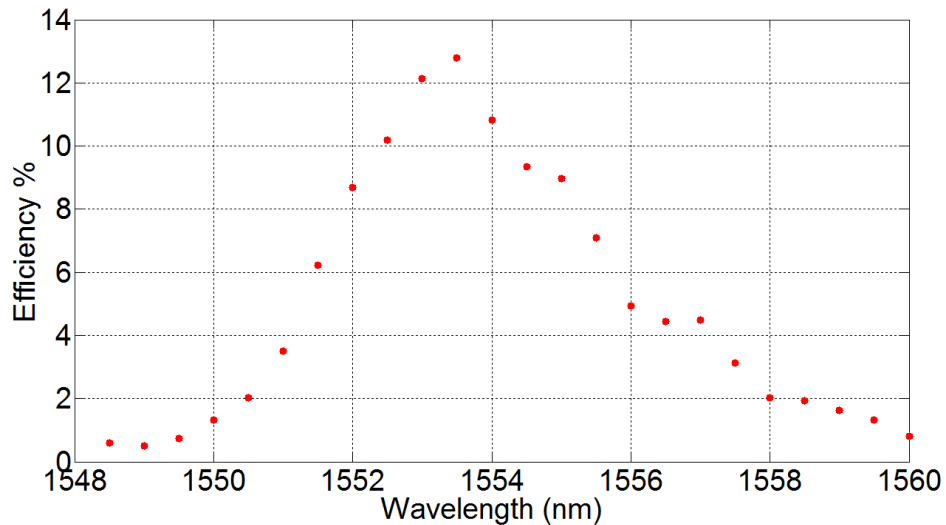


Figure 8. Diffraction efficiency as a function of the wavelength.

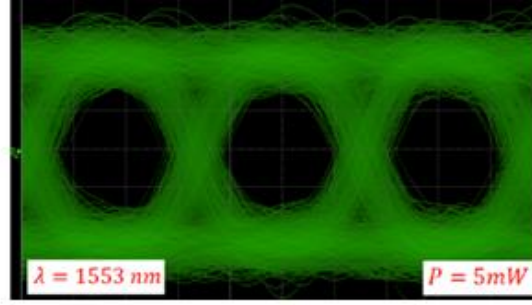


Figure 9. Eye diagram for an infrared launched power of $P = 5mW$.

as the modulated carrier. The reading beam was modulated using a 625Mbps Pseudo-Random Bit Stream (PRBS) and Non-Return to Zero (NRZ) On-Off-Keying (OOK). A captured open eye diagram is shown in Figure 9. A Bit Error Ratio (BER) measurement was undertaken, giving BER values below 10^{-6} .

The hologram grating written with the He-Ne lasers degraded in time in a natural erasure process dependant on the crystal properties. The strength of the communications link was tested for a period of 9 hours. The launched optical power was fixed so that the initial BER was close to 10^{-6} . The experimental data is plotted in Figure 10 showing some degradation in performance. This

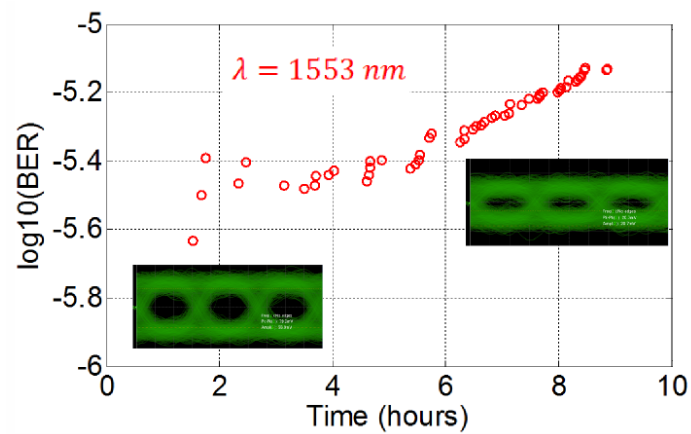


Figure 10. BER degradation in time.

suggests that depending on the application, the hologram writing process will have to be repeated to recover a desired BER performance.

2.4.3 Conclusions from feasibility study

This experiment demonstrates, for the first time to the best of our knowledge, the feasibility of a high speed infrared link using a PR crystal as the beamsteerer. However, “programming” this beamsteerer requires a means to control the direction of the writing beams, i.e. the need of a beamsteerer in the visible spectrum. Moreover, LiNbO₃ and other PRs are uniaxial crystals. Thus, the corresponding birefringence effect varies the grating strength as a function of the grating vector $\mathbf{K}$. This further complicates the implementation of a practical system.

Finally, keeping the same LiNbO₃ crystal the DPCM effect was investigated. Visible laser beams were used to maximise the material’s response. However, the effect could not be generated. Thus, these materials were unfeasible as beamsteerers for the fibre-based transceivers defined in Figure 4.

2.5 SLM HOLOGRAPHIC BEAMSTEERING

Another approach to generate diffraction gratings for beamsteering is to use SLM technology. The availability of liquid crystal (LC)-SLMs with integrated drivers make these steering devices the most suitable for the laboratory experiments and test-beds. These are expensive components but represent a proven technology [60], [61] whose cost can be substantially reduced if produced in numbers. They also provide the potential to carry out adaptive optics functions as will be shown in the following sections.

This section provides an introduction to SLM beamsteering. A nematic off-the-shelf LC-SLM is characterized. Simulations and preliminary experiments are carried out to determine the beamsteering capabilities. A passive angle magnification scheme is later introduced in order to enhance the steering system FOV to a practical range. Finally, a brief discussion is included to show the need of adaptive optics in the correction of geometrical aberrations in the optical magnification system.

2.5.1 Liquid crystal spatial light modulator

LC-SLMs are spatially arrayed devices capable of independently controlling the phase and / or amplitude of an incident beam for each pixel in the array. Devices can work both in transmission and reflection, and for a reflective configuration, a schematic is shown in Figure 11. A coherent

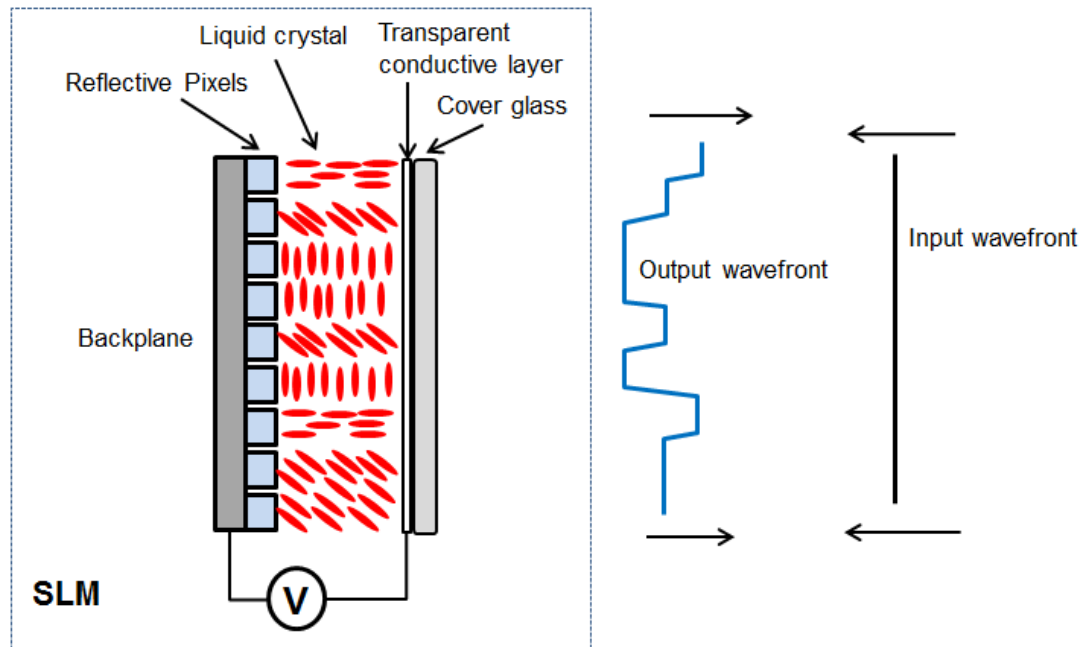


Figure 11. Cross section schematic of an LC-SLM. The device is typically a 2D pixelated array.

and polarized beam illuminates the LC-SLM. The input light passes through the cover glass and a transparent conductive layer, and propagates through the LC. The reflective array of pixels then acts as a mirror to send the light back on the same path in the opposite direction.

Analogue voltages can be independently applied to each pixel via backplane circuitry. This produces an electric field across the LC with a spatial resolution given by the pixel pitch. The electric field changes the optical properties of the LC and a phase pattern can be imprinted on the illuminating wavefront by loading different voltages onto each pixel. Inter-pixel modulation cross-talk may occur from voltages applied to adjacent pixels. This effect is unwanted but present in commercial devices.

In this thesis, a nematic uniaxial LC-SLM is used with the LC molecules aligned in a

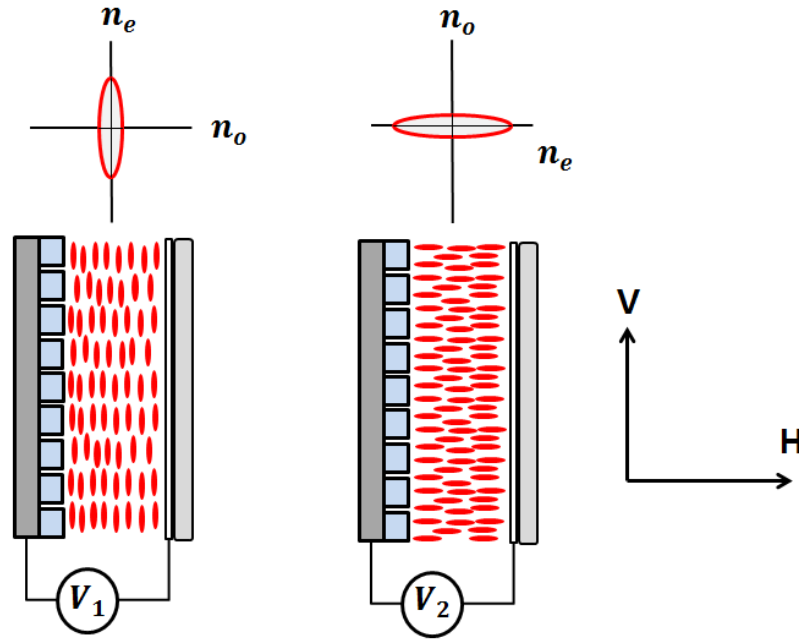


Figure 12. Nematic LC electro-optical response for a uniaxial case. Voltage V_1, V_2 change the LC orientation. n_o and n_e are the ordinary and extraordinary refractive indexes of the uniaxial LC.

homogeneous configuration. These LCs present a variable electro-optic response as a function of the applied electric field [62][63]. Figure 12 shows an LC-SLM schematic. All pixels are driven with uniform voltage V for simplicity. When V_1 is applied, the LC molecules are parallel to the vertical (V) axis; whereas for voltage V_2 the orientation of the molecules change by 90° . As a result, the effective refractive index n_{eff} in the V direction changes by as much as $|n_e - n_o|$. This birefringence produces a pure phase shift in the incident wavefront, provided the light is linearly polarized in the V direction [50]. A voltage vs. phase calibration as a function of the wavelength of operation allows for a precise phase modulation. This configuration will be referred to as phase-only mode.

Therefore, given an SLM plane with transverse coordinates (x, y) and normally incident light defined by $U_I = U_0 \cdot \exp[i \cdot \varphi_0(x, y)]$, then the reflected wavefront can be described as,

$$U_F = U_0 \cdot \exp[i \cdot (\varphi_0(x, y) + \varphi_{SLM}(x, y))] \quad (3)$$

Where $\varphi_{SLM}(x, y)$ is the phase profile added by the SLM. The phase-only LC-SLM functionality can be theoretically modelled using scalar coherent wave propagation theory. The next section introduces this theory outlining some relevant properties applicable to LC-SLMs. The device pixelated nature will also be considered.

2.5.2 Coherent wave propagation theory

Let us consider a coherent light distribution U defined by a complex field in amplitude and phase. The field propagation along the optics axis Z is sketched in Figure 13. The field at $z = 0$ and after an axial propagation of z is $U(x', y', z = 0)$ and $U(x, y, z)$, respectively. It can be shown that the

time-independent solution to the Helmholtz equation $((\nabla^2 + k^2)G(x, y) = 0)$ can take the form [64],

$$U(x, y, z) = \iint_{-\infty}^{\infty} \tilde{U}(u, v) \exp[2\pi i(xu + yv + zw)] du dv \quad (4)$$

$$u^2 + v^2 + w^2 = \lambda^{-2}$$

$$\tilde{U}(u, v) = \iint_{-\infty}^{\infty} U(x', y', z = 0) \exp[-2\pi i(ux' + vy')] dx' dy' \quad (5)$$

Where $\tilde{U}(u, v)$ is the two dimensional spectrum of the field $U(x, y, z = 0)$, λ is the monochromatic wavelength and (u, v, w) are the normalized spectral coordinates. Physically, $\tilde{U}(u, v)$ is the amplitude of a plane wave that propagates in the (u, v) direction, i.e. (u, v) are the direction cosines of the plane wave. Therefore, the field distribution in the plane $Z = z$ is the coherent sum of the individual plane waves over all directions weighted by the spectral amplitude

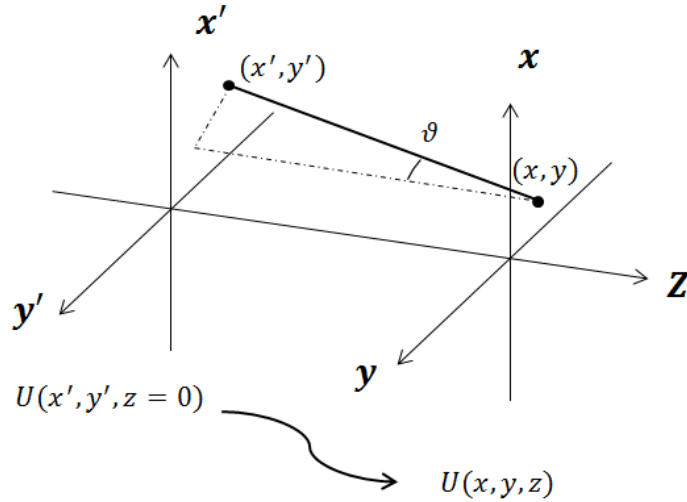


Figure 13. Propagation of field U . The optical axis is Z and the observation point (x, y, z) .

$\tilde{U}(u, v)$. Equation (4) can be conveniently rearranged as follows:

$$U(x, y, z) = \iint_{-\infty}^{\infty} \tilde{U}(u, v) \exp \left[2\pi i z \sqrt{\lambda^{-2} - u^2 - v^2} \right] \exp[2\pi i(xu + yv)] du dv \quad (6)$$

Equation (6) shows that the field distribution in the plane $Z = z$ is the inverse Fourier transform of $\tilde{U}(u, v) \exp[2\pi i z \sqrt{\lambda^{-2} - u^2 - v^2}]$. Analytical solutions using this angular spectrum approach is cumbersome. However, numerical computations of the diffracted field can be realized. The following procedure gives a good approximation for discretised fields as long as the Shannon-Whittaker sampling theorem is satisfied [64]:

1. Take the initial field $U(x, y, z = 0)$ and calculate the 2D discrete Fourier transform (2D-DFT). The result is $\tilde{U}(u, v)$ as shown in equation (5) for the continuous case.
2. Multiply $\tilde{U}(u, v)$ by the propagation factor $\exp[2\pi i z \sqrt{(\lambda^{-2} - u^2 - v^2)}]$
3. Calculate the inverse 2D-DFT of $\tilde{U}(u, v) \exp[2\pi i z \sqrt{(\lambda^{-2} - u^2 - v^2)}]$, which is a discrete form of equation (6).
4. The field distribution $U(x, y, z)$ in the plane $Z = z$ is estimated.

The angular spectrum integrals shown in equations (4) and (5) accurately describe the diffraction of light for coherent optical illumination. A less rigorous but useful expression can be deduced by considering the following approximations (see Figure 13 for the variables' definitions): $z \gg \lambda$ and

$$\left\{ \sqrt{x^2 + y^2} \ll z \ \& \ \sqrt{x'^2 + y'^2} \ll z \right\} \Rightarrow \cos \vartheta \approx 1. \quad \text{That is, the observation plane is far with}$$

respect to the wavelength of operation, and also the observation point (x, y) and integration points (x', y') are relatively close to the optical axis. As a result, the following formula (some constant phase factors are omitted) is obtained:

$$U(x, y, z) \propto \iint_{-\infty}^{\infty} U(x', y') \exp \left[-\frac{ik}{2z} (x'^2 + y'^2) \right] \exp \left[-\frac{ik}{z} (xx' + yy') \right] dx' dy' \quad (7)$$

$$U(x, y, z) \propto \tilde{U}'(m, n) \big|_{m=\frac{x}{\lambda z}, n=\frac{y}{\lambda z}} \quad \text{with} \quad \tilde{U}'(m, n) = \mathcal{F} \left\{ U(x', y') \exp \left[\frac{ik}{2z} (x'^2 + y'^2) \right] \right\}$$

Where $\mathcal{F}\{G\}$ is the Fourier transform of G . Equation (7) is referred to as the Fresnel diffraction integral. A further simplified expression is possible assuming that $x'^2 + y'^2 \ll xx' + yy'$, i.e. the integration over the plane $z = 0$ is confined to a small area. In this case, the Fresnel integral is reduced to:

$$U(x, y, z) \propto \iint_{-\infty}^{\infty} U(x', y') \exp \left[-\frac{ik}{z} (xx' + yy') \right] dx' dy' \quad (8)$$

$$U(x, y, z) \propto \tilde{U}'(m, n) \big|_{m=\frac{x}{\lambda z}, n=\frac{y}{\lambda z}} \quad \text{with} \quad \tilde{U}'(m, n) = \mathcal{F}\{U(x', y')\}$$

Equation (8) is known as the Fraunhofer diffraction integral. The Fraunhofer field distribution is simply the scaled Fourier transform of the initial field at $z = 0$. Choosing the right diffraction integral is important to obtain reliable results in numerical simulations. The angular spectrum integral is the most exact approach. However, computational costs particularly in iterative algorithms may require simpler equations such as the Fresnel or the Fraunhofer approximations.

Finally, when applying the previous theory to the LC-SLM, a discrete version of the model is needed to account for the pixelated nature of the device. Let us consider $U(x', y', z = 0)$ and $U(x, y, z)$ the optical fields in the SLM and reflected wavefront planes, respectively. Let us assume that the SLM active area is defined by an N by N squared array with side $L_{SLM} = N \cdot \Delta p$, Δp being the SLM pixel pitch. After a propagation distance z , the reflected wavefront can be sampled over an equivalent squared zone with side $L_r = N \cdot \Delta r$, where $\Delta r = \lambda z / (\Delta p \cdot N)$ is the

new array pitch, the later fixed by the Nyquist sampling limit [64]. Provided uniform illumination, a discrete version of equation (8) can be shown to be [65]:

$$U(r \cdot \Delta r, s \cdot \Delta r, z) \propto \text{sinc}\left(\frac{r}{N}\right) \cdot \text{sinc}\left(\frac{s}{N}\right) \cdot DFT(r, s) \quad (9)$$

$$\text{with } DFT(r, s) = \frac{1}{N^2} \cdot \sum_{m=-\frac{N}{2}}^{\frac{N}{2}-1} \sum_{n=-\frac{N}{2}}^{\frac{N}{2}-1} \left\{ U(m\Delta p, n\Delta p, z=0) \cdot \exp\left[-i \frac{2\pi}{N}(mr + ns)\right] \right\}$$

Where $(r, s) \in \left[-\frac{N}{2}, \frac{N}{2} - 1\right]$. The DFT is the well-known discrete Fourier transform. The sinc functions ($\text{sinc}(a) = \frac{\sin(\pi a)}{\pi a}$) act as a spatial filter and it is a direct consequence of the discretization. If the illumination field in the SLM is defined as $U_A(m\Delta p, n\Delta p, z=0) = A(m, n) \exp[\alpha(m, n)]$, then the field just after the SLM is modified to:

$$U(m\Delta p, n\Delta p, z=0) = A(m, n) \exp[\alpha(m, n) + \rho_{SLM}(m, n)] \quad (10)$$

Where $\rho_{SLM}(m, n)$ is the phase modulation added by the SLM pixel (m, n) . It is straightforward to show the linear property of the DFT in equation (9) with respect to the phase $\rho_{SLM}(m, n)$ in equation (10) in modulo 2π . As a result, several SLM phase profiles corresponding to different effects can be added up resulting in the coefficient $\rho_{SLM}(m, n) = \exp[i \cdot \sum_{j=1}^l \vartheta_j(m, n)]$. Each ϑ_j profile may correspond to a function, e.g. beamsteering, adaptive optics, etc, all of which can be applied simultaneously. A limiting factor to consider is the phase quantization. In commercial SLMs, each pixel will have M possible phase values over a range of $[0, 2\pi]$ for the designed wavelength of operation. Typically, the number of phase levels vary from binary (0 or π phase, $M = 2$) to practically analogue ($M > 128$). In this work, an analogue SLM is studied. In the next section, the corresponding beamsteering characterization is performed.

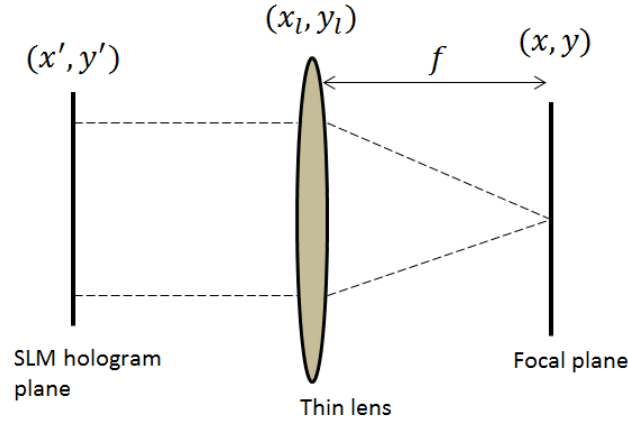


Figure 14. SLM and thin lens model. The thin lens' focal length is f and the SLM is located in the back focal plane.

2.5.3 Analogue SLM beamsteering characterization

In this thesis, a 512x512 SLM array optimised for 1550 nm operation (BNS HSP512-1550, pixel size $p = 15 \mu m$) is used. Even though higher resolution (smaller pixels) and larger active areas devices are desirable, the technological challenges limited the commercial availability to the given specifications. This SLM uses nematic LC and allows a maximum of 2π phase shift per pixel, with $M = 256$ phase levels to be programmed. In this analogue SLM, the beamsteering function can be quickly implemented using a ramp phase profile defined as follows:

$$\begin{aligned} Ramp &= \pi \eta r_N \\ \eta &= \frac{N}{2} \frac{\varphi_{SLM}}{\varphi_{max}} \quad ; \quad \varphi_{max} = \lambda / (2p) \end{aligned} \quad (11)$$

Where $N = 512$ is the SLM's number of pixels and $r_N = r / (N/2)$, $r = \{-N/2 \dots N/2 - 1\}$ is the normalized radial pixel coordinate whose origin is at the centre of the SLM. In order to interpret equation (11), let us consider Figure 14 where an SLM followed by a single lens with focal length f is given. Using a thin lens model the transmittance function is given as,

$$t(x_l, y_l) = \exp[-(ik/2f)(x_l^2 + y_l^2)] \quad (12)$$

It can be shown that the relationship between the SLM and focal planes is described by equation (8) with a scale of $m = x/\lambda f$, $m = y/\lambda f$. That is, the lens transforms the field in the SLM plane via a scaled Fourier transform into a reciprocal space located in the focal plane. Thus, using the property of Fourier transforms $\mathcal{F}\{f(x') \cdot \exp(-i2\pi ax')\} = F(u - a)$ it can be seen that a phase ramp hologram (equation (11)) in the SLM plane is equivalent to a beamsteering action in the reciprocal plane, irrespective of the SLM illumination profile.

The SLM beamsteering was quantitatively characterized in simulations. The problem was set as follows. First, a Gaussian beam with beam waist $\omega = 7 \text{ mm}$ and approximately uniform phase illuminates the SLM. A phase ramp is programmed on the SLM varying the steering factor r_N in equation (11). After the SLM, the beam propagates for $z = 100 \text{ mm}$ where a lens with focal

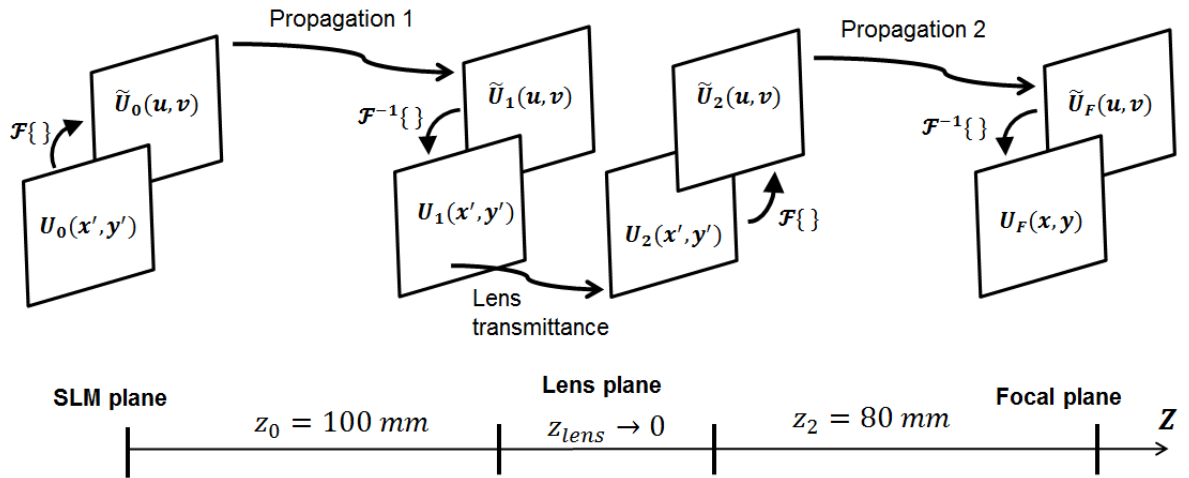


Figure 15. Angular spectrum simulation. The diagram shows the transformation steps to connect the SLM and focal planes fields $U_0(x', y')$ and $U_F(x, y)$, respectively. The symbols $\mathcal{F}\{\}$ and $\mathcal{F}^{-1}\{\}$ represent the discrete Fourier transform (DFT) and inverse DFT, respectively.

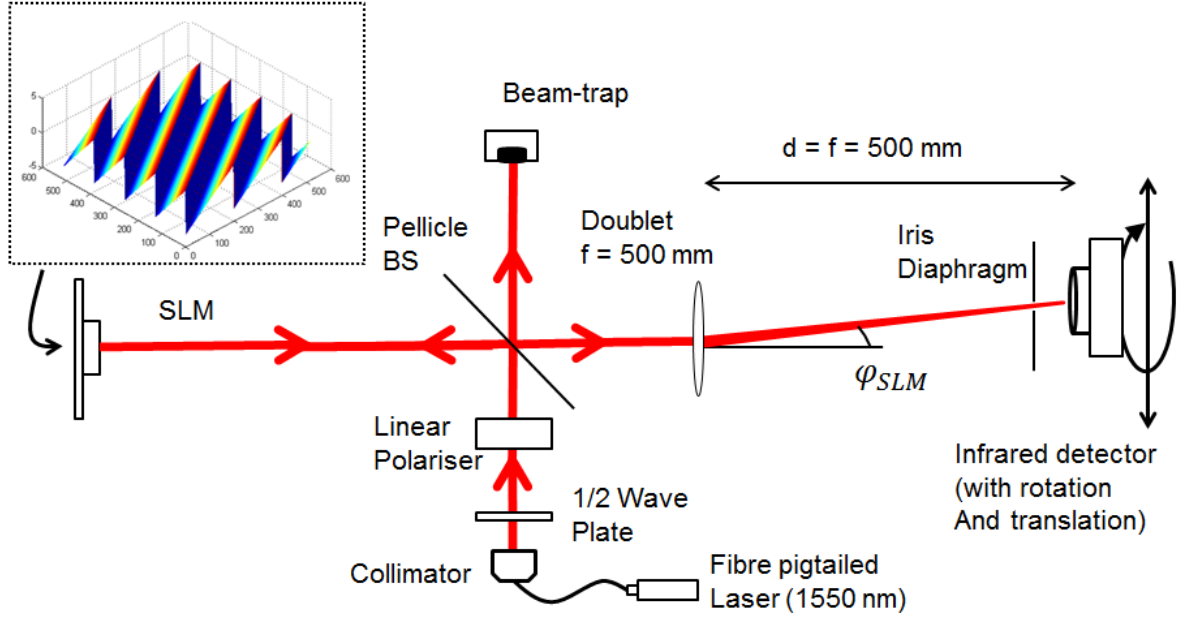


Figure 16. SLM beamsteering characterization. The inset figure represents an SLM sawtooth phase profile varying from 0 to 2π . BS is a beamsplitter.

length $f = 80 \text{ mm}$ focuses the beam in the focal plane. Using the angular spectrum propagation theory developed in the previous section, the beamsteering action was accurately estimated in the lens focal plane using the SLM ramp phase modulation. The detailed procedure is shown in Figure 15. The lens transmittance function is given by equation (12) and the propagation along the optical axis is carried out in the spectral domain.

To have a preliminary comparison with the simulations, the SLM beamsteering was also experimentally characterized for a similar setup to that shown in Figure 14. This time a lens with $f = 500 \text{ mm}$ was used to further increase the beam walk off in the focal plane as shown in Figure 16. For the experimental setup, a 1550 nm laser is collimated and vertically polarized. This then illuminates the SLM. The beam footprint is $\sim 7 \text{ mm}$, filling the device square active area of $7.2 \text{ mm} \times 7.2 \text{ mm}$. The beamsteering function is achieved by adding a ramp phase to the SLM as those defined by equation (11). Due to the phase modulation constraint of the LC, this phase ramp is fed

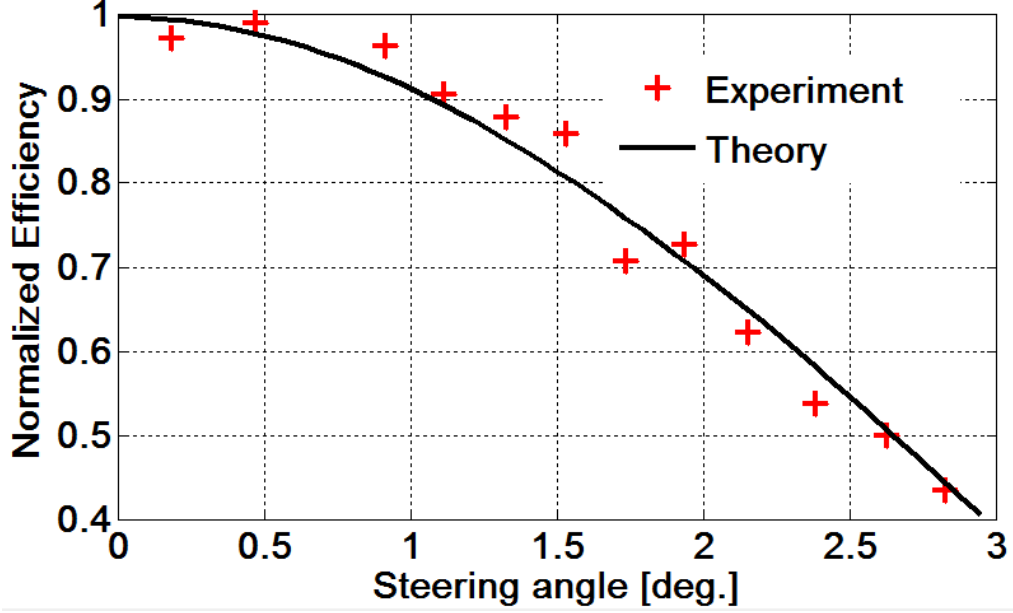


Figure 17. SLM normalized steering efficiency as a function of the beamsteering angle. The normalization is carried out with respect to the total incident power on the SLM.

to the SLM as a saw-tooth profile capped between $[0, 2\pi]$ as shown in Figure 16 inset. Finally, the light reflected from the SLM is focused onto an infrared detector.

In summary, combining the experimental and simulation results described in this section, Figure 17 shows the SLM beamsteering characterization. The steering efficiency is plotted as a function of the SLM steering φ_{SLM} . The experimental and theoretical data are in good agreement. There is a drop proportional to $\text{sinc}^2(\varphi_{SLM}/\varphi_{max})$ as predicted by equation (9), and the steering range coincides with the theoretical expectation of $\varphi_{max} = \lambda/(2p) = 3^\circ$.

2.6 ANGLE MAGNIFICATION

For an indoor wireless application, a wide angle beamsteering system is needed. The achievable beamsteering angle using the BNS SLM is limited to $\varphi_{SLM} = \pm 3^\circ$. Therefore, an angle magnification (AM) module is required to enhance the FOV from $\pm 3^\circ$ to a higher value, e.g. $\pm 30^\circ$.

A passive AM can be implemented using a two-lens optical system as shown in Figure 18 (a). The schematic is an afocal setup where lenses L_1 and L_2 share the intermediate focal plane. A modified configuration is proposed here (Figure 18 (b)), which includes a field lens L_C located in this intermediate plane. This lens L_C images L_1 's aperture onto that of L_2 . As a consequence, L_C centres the incoming beam footprint on lens L_2 , and this in turn reduces the geometrical aberrations [66]. Using thin lens imaging, non-paraxial ray tracing and trigonometric arguments:

$$\frac{1}{f_1} + \frac{1}{f_2} = \frac{1}{f_C} \quad ; \quad M_C = \frac{f_2}{f_1} = \frac{\omega_{OUT}/\cos \theta_{OUT}}{\omega_{IN}/\cos \varphi_{IN}} \quad ; \quad f_1 \tan \varphi_{IN} = f_2 \tan \theta_{OUT} \quad (13)$$

M_C refers to the image magnification of lens L_C . Equation (13) can be used to design the AM module starting from a required angular magnification $\gamma = \theta_{OUT}/\varphi_{IN}$. Also, the following important condition can be deduced from the same equation (see Figure 18 to recall the variable's definitions):

$$\omega_{OUT} \cdot g(\theta_{OUT}) = \omega_{IN} \cdot g(\varphi_{IN}) \quad ; \quad \text{with } g(\alpha) = \tan \alpha / \cos \alpha \quad (14)$$

Equation (14) fixes $\omega \cdot g(\alpha) = \text{constant}$. This is a result of etendue conservation [44]. In the paraxial approximation regime $g(\alpha) = \alpha$ and $\omega_{OUT} \cdot \theta_{OUT} = \omega_{IN} \cdot \varphi_{IN}$. Thus, an angular magnification of $\gamma = \theta_{OUT}/\varphi_{IN}$ implies a beam width de-magnification of $\omega_{OUT}/\omega_{IN} = 1/\gamma$. The implications of this relationship are not straightforward, and will be studied in the next chapter as part of the overall link model.

The next section briefly explains how to improve the AM model when using real lenses as opposed to ideal thin lens components.

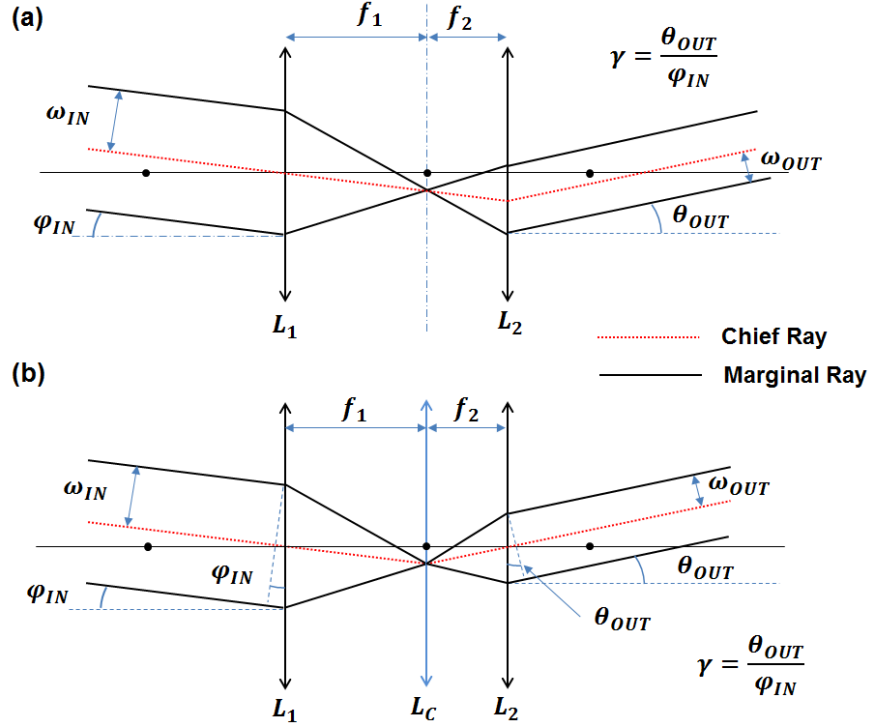


Figure 18. AM afocal system with magnification $\gamma = \theta_{OUT}/\phi_{IN}$ for (a) a simple two-lens configuration and (b) a 3-lens setup using a field lens L_c .

2.7 ADAPTIVE OPTICS REQUIREMENTS

So far the thin lens approximation has been used for all optical lenses in the AM. This has allowed us to neglect geometrical aberrations added by real lenses with physical thicknesses and spherical curvatures. As the SLM beamsteering angle is increased, strong distortions within the AM module are expected. This is particularly relevant for our proposed SMF fibre-pigtailed receiver design where the power coupling efficiency depends on beam profile in amplitude and phase as outlined in section 2.2.

As a first step, aberrations can be reduced in the AM using aspheric lenses and doublets. These are more expensive components compared to, e.g. plano-convex spherical lenses, but they

substantially reduce the AM distortions. Therefore, in the realization of the AM described in the next chapter aspheric / doublets lenses were used if permitted by the design.

However, residual geometric aberrations will be present, particularly for large angle beamsteering. In principle, these aberrations can be quantified as a function of the beamsteering angle. Thus, pre-compensation for aberrations can be set in the SLM by combining the phase ramp hologram (beamsteering) with additional phase profiles that cancel the wavefront distortions. This is possible due to the phase linearity of an SLM (in modulo 2π) as discussed in section 2.5.2.

In adaptive optics systems the aberrations are usually characterized using Zernike polynomials [67], [68]. These are orthogonal phase profiles that can be linearly combined to compensate for aberrations in a circularly symmetric optical system. Relevant 1st order Zernike polynomials are listed below [67],

$$\begin{aligned}
Z_{def} &= C_{def} \cdot \sqrt{3}(2x_N^2 + 2y_N^2 - 1) \\
Z_{sph} &= C_{sph} \cdot \sqrt{5}(6x_N^4 + 12x_N^2y_N^2 + 6y_N^4 - 6x_N^2 - 6y_N^2 + 1) \\
Z_{coma,x} &= C_{cx} \cdot \sqrt{8}(3y_N^2x_N + 3x_N^3 - 2x_N) \quad Z_{coma,y} = C_{cy} \cdot \sqrt{8}(3x_N^2y_N + 3y_N^3 - 2y_N) \\
Z_{astig,x} &= C_{ax} \cdot \sqrt{6}(X_N^2 - 2Y_N^2) \quad Z_{astig,y} = C_{ay} \cdot \sqrt{6}(2X_N^2Y_N^2)
\end{aligned} \tag{15}$$

Where x_N, y_N are the normalized optical system pupil coordinates and $Z_{def}, Z_{sph}, Z_{coma}$ and Z_{astig} are the defocus, spherical, coma, and astigmatism polynomials. The coefficients C_X are non-dimensional and can be considered weighting factors. It is expected that a combination of the polynomials listed in equation (15) will compensate for aberration, at least to the 1st order as higher order Zernike polynomials will not be used.

Chapter 3

Single link communications

3.1 OVERVIEW

Following the SLM holographic beamsteering characterization in Chapter 2 here a wide FOV FWF link is designed and implemented. A combination of SLM active beamsteering with AM passive magnification is used. A model is presented to determine the relationship between the link loss and the SLM active beamsteering capabilities, given a required coverage area (defined by the link range Z and FOV).

In this chapter, the FWF design is maximized to achieve a FOV of $\theta_{FOV} = \pm 30^\circ$ at a range of 3 m whilst maintaining acceptable link loss margins for data rates greater than 200 Gb/s. A 400 Gb/s FWF link with a $\theta_{FOV} = \pm 20^\circ$ using a state-of-the-art coherent transmission system is also demonstrated. To the best of our knowledge, this is the fastest wireless demonstration with a realistic coverage area that allows for nomadic indoor applications.

3.2 LINK MODEL

A symmetric FWF link is proposed as shown in Figure 19. Coherent light collimated from an optical fibre illuminates a Tx SLM. The device's effective aperture is $2\omega_0$ and the steering capability is $\pm\varphi_0$. The reflected light from the SLM enters an angle magnification (AM) unit enhancing the link FOV θ_{FOV} by a factor of $\gamma_0 = \theta_{FOV}/\varphi_0$. From equation (14) the beam size exiting the AM is fixed at $\omega_{Tx} = \omega_0 \cdot g(\varphi_0)/g(\theta_{FOV})$. The output beam then propagates in free space for a distance Z , whilst experiencing beam spreading due to diffraction. Using classical Gaussian beam propagation theory [69], then the beam spot size at the receiver ω_{Rx} is given by:

$$\omega_{Rx} = \omega_{Tx} \sqrt{1 + (Z/Z_{Tx})^2} \quad (16)$$

Here $Z_{Tx} = \pi \omega_{Tx}^2 / \lambda$ is the Rayleigh length of the Gaussian beam in free space. After the receiver aperture, a symmetric AM de-magnifies the beam angle by $\gamma_1 = \theta_{FOV} / \varphi_1$ where $\pm \varphi_1$ is the Rx SLM steering range. In doing so, the beam width ω_{AM} is magnified according to equation (14) as $\omega_{AM} = \omega_{Rx} \cdot g(\theta_{FOV}) / g(\varphi_1)$ due to etendue conservation (refer to section 2.6). This wider beam creates a vignetting loss $\mathcal{L}_V$ in the Rx SLM with aperture size ω_1 if $\omega_{AM} > \omega_1$. Finally, the Rx SLM steers the beam back into an optical fibre. Light then propagates to a fibre pigtailed receiver. The coupling loss $\mathcal{L}_F$ at the facet of the Rx fibre is considered in later sections once the AM system is further specified. The link's geometrical loss $\mathcal{L}_V$ due to vignetting can be determined as a function of the Tx and Rx etendues, $\mathcal{E}_{Tx}$ and $\mathcal{E}_{Rx}$ respectively, conveniently defined as follows:

$$\begin{aligned} \mathcal{E}_{Tx} &= \pi \omega_0^2 g^2(\varphi_0) = \pi \omega_{Tx}^2 g^2(\theta_{FOV}) \\ \mathcal{E}_{Rx} &= \pi \omega_1^2 g^2(\varphi_1) = \pi \omega_{Rx}^2 g^2(\theta_{FOV}) \end{aligned} \quad (17)$$

Based on the diagram depicted in Figure 19, and using equations (16) and (17) the following relationships can be deduced:

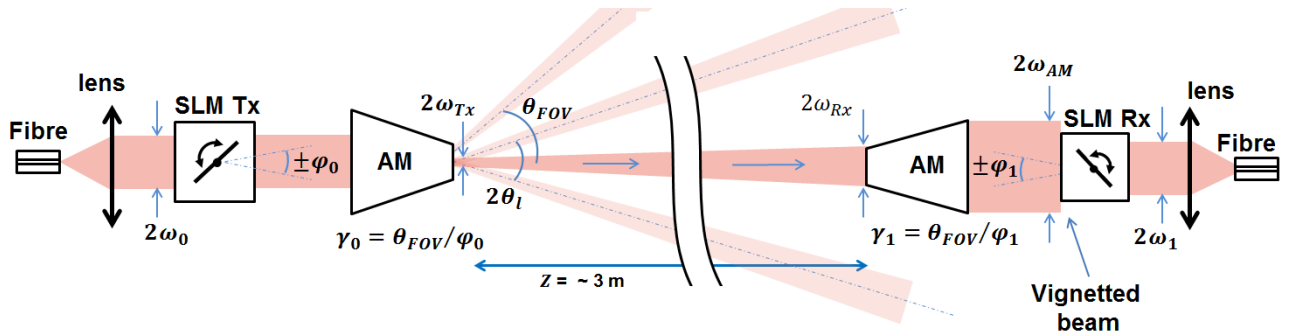


Figure 19. Link design. AM is an angle magnifier and SLM is a spatial light modulator.

$$\begin{aligned}\mathcal{L}_{DL} &= 10 \log_{10}(\mathcal{E}_{Tx} \cdot \mathcal{E}_{Rx}) - 10 \log_{10}(\mathcal{E}_{Tx}^2 + \lambda^2 Z^2 g^4(\theta_{FOV})) \\ \mathcal{L}_{UL} &= 10 \log_{10}(\mathcal{E}_{Tx} \cdot \mathcal{E}_{Rx}) - 10 \log_{10}(\mathcal{E}_{Rx}^2 + \lambda^2 Z^2 g^4(\theta_{FOV}))\end{aligned}\tag{18}$$

Here, $\mathcal{L}_{DL} = (\omega_1/\omega_{AM})^2$ and $\mathcal{L}_{UL} = (\omega_0/\omega_{AM})^2$ are the downlink and uplink losses, respectively, for a generalized bidirectional configuration. A qualitative analysis of equation (18) shows that the higher the design θ_{FOV} and the link range Z are, then the higher $\mathcal{L}_V$ will be. This outlines the challenge of designing a functional bidirectional link as the indoor link coverage is increased.

3.2.1 Symmetric link study

A symmetric link with identical beamsteering units at both transceivers is studied. The free space transceiver's separation is fixed to $Z = 3$ m in accordance with a typical room's dimensions. For a symmetric link (SL) where $\mathcal{E}_{Tx} = \mathcal{E}_{Rx}$, the characteristic link loss is $\mathcal{L}_V = \mathcal{L}_{DL} = \mathcal{L}_{UL}$. Figure 20 shows a contour plot of $\mathcal{L}_V$ as a function of the link's FOV and $\sqrt{\mathcal{E}} \sim \omega \cdot g(\varphi)$ defined by equation (14). $\sqrt{\mathcal{E}}$ is a figure of merit (FOM) for an active beamsteering device: the higher this product is, the lower the losses in our model.

Recalling the SLM steering characterization in section 2.5.3, the beamsteering range is $\varphi_0 = \pm 3^\circ$ and $\omega_0 = 3.5$ mm. This gives a FOM $\omega_0 \cdot g(\varphi_0) = 2 \cdot 10^{-4} \text{ m} \cdot \text{rad}$. For this FOM, $\mathcal{L}_{SL}$ strongly increases as a function of the link's FOV, e.g. by 10 dB when the link's FOV rises from 30° to 45° . Thus, a good compromise between the link coverage and the geometrical loss can be achieved at $Z = 3$ m and $\theta_{FOV} = 30^\circ$, i.e an angular magnification of $\gamma = \theta_{FOV}/\varphi_{SLM} = 10$. This conclusion is a key design point for later sections.

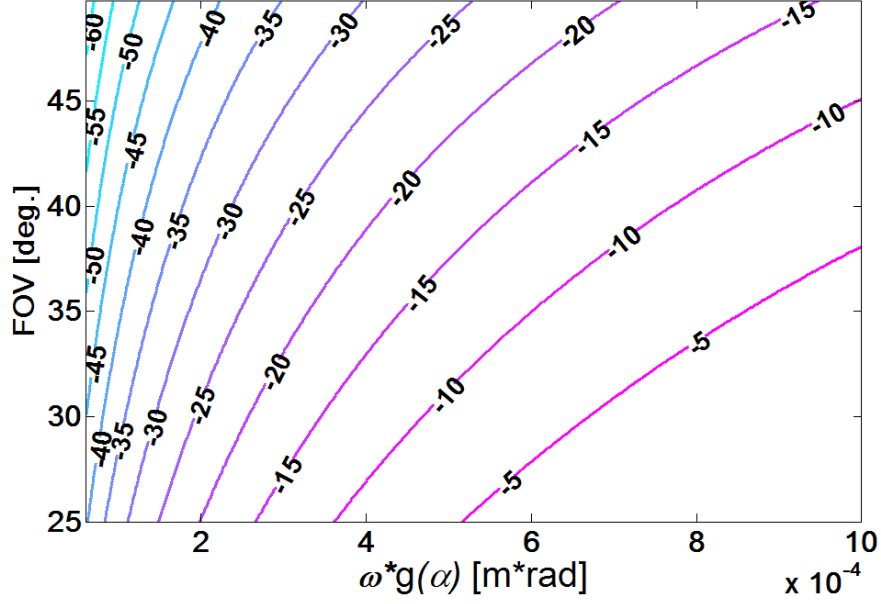


Figure 20. Characteristic loss $\mathcal{L}_V$ in decibels (dB) for a symmetric link. The free space range is $Z = 3$ m. The contour lines represent the loss levels in dB as a function of the FOV and the product $\sqrt{\mathcal{E}} \sim \omega \cdot g(\alpha)$. Here ω and α are the active steering device's aperture radius and steering range, respectively.

3.3 ANGLE MAGNIFICATION DESIGN

The link loss model studied in the previous section determined an achievable $\theta_{FOV} = 30^\circ$ using active SLM beamsteering with $\varphi_0 = \pm 3^\circ$ and $\omega_0 = 3.5$ mm. The link FOV is enhanced with passive angular magnification. In this section, a suitable AM with commercial lenses is designed and characterized. The model is validated using ray tracing in Zemax[®] for an SMF fibre-pigtailed receiver.

Recalling the AM theory developed in section 2.6, equation (13) can be used to design an afocal system with a field lens f_C . Knowing that $\gamma = \theta_{FOV}/\varphi_{SLM} = 10$ it can be calculated that $f_1/f_2 = 11$. Using off-the-shelve lens components, Figure 21 shows a valid AM schematic realization. The focal length $f_C \sim 7$ mm was chosen from $1/f_C = 1/f_1 + 1/f_2$, with $f_1 = 77$ mm and $f_2 = 8$ mm.

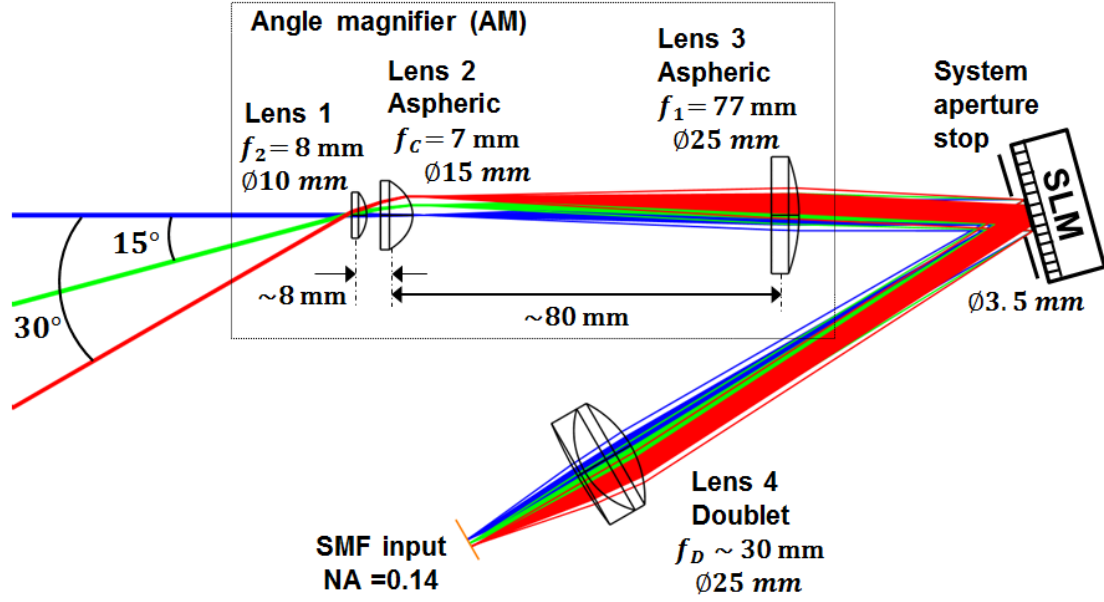


Figure 21. Zemax layout of the ray tracing through the AM, SLM in reflection, and finally a doublet focusing the light onto the SMF input facet. There are three angular fields present: 0° , 15° and 30° . Lens 1 and 2 are Edmund optics components with part numbers 84230 and 47725, respectively. Lens 3 and 4 are Thorlabs components with part numbers ASL10142M-C and AC254-035-C, respectively.

All f values are given at $\lambda = 1550$ nm and they are referenced to the back focal plane, i.e. the planar surface of each lens.

Zemax[®] was used to model the AM as a function of the input field angle θ_i as shown in Figure 21. For the simulations, an incoming beam with uniform power and planar wavefront was set. The AM output then illuminated an SLM in an off-axis configuration, followed by a collimator focusing the beam onto an SMF fibre facet. The SLM was modelled as a 512×512 phase array where the pixelation loss, phase quantization and inter-pixel crosstalk are ignored (refer to section 2.5 for more details on phase-only SLM modelling). The SLM beamsteering was achieved by setting a continuous ramp phase profile as described by equation (11). Simulation results are

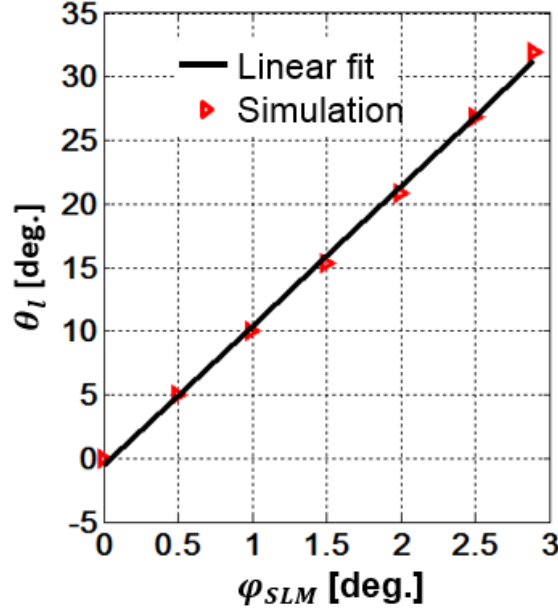


Figure 22. AM simulation results. The relationship between the link angle θ_l and the SLM beamsteering φ_{SLM} is given. The curve's slope corresponds to the AM magnification.

shown in Figure 22. Figure 22 (a) gives the relationship between the SLM steering angle φ_{SLM} and the link angle θ_l such that the power coupling into the fibre is maximized. The trend is quasi-linear with $\gamma \sim 10$, which validates the design.

3.3.1 AM aberration correction

The AM design shown in Figure 21 requires compensation for geometrical aberrations in order to optimize the power coupling into the SMF fibre. These aberrations are wavefront distortions that vary over the link FOV. Figure 23 shows the simulated wavefront at the facet of the SMF fibre for different link angles. It can be seen that a wavefront distortion as large as 1.33 waves ($\lambda = 1550 \text{ nm}$) is present at $\theta_l = 30^\circ$ compared to only 0.05 waves at $\theta_l = 0^\circ$. This is an indication of adaptive optics requirements as a function of θ_l .

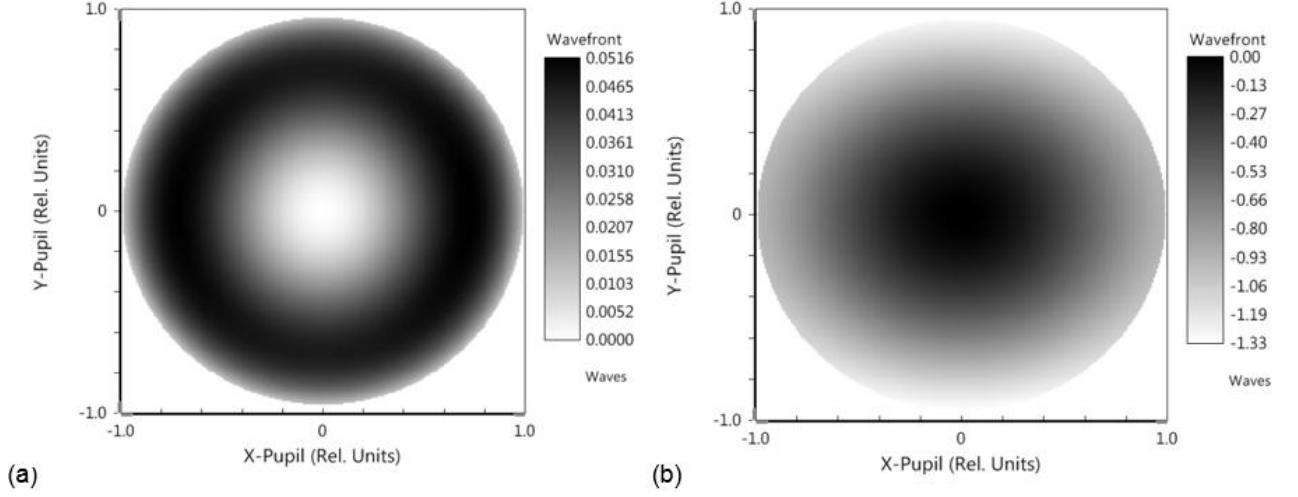


Figure 23. Wavefront distortion plot in the SMF fibre plane for (a) $\theta_l = 0^\circ$ and (b) $\theta_l = 30^\circ$

To quantify the effect of the wavefront constrast on the SMF power coupling, the normalized overlap integral between the fibre propagation mode and the incident wavefront was numerically estimated in Zemax[®] (see section 2.2). An SMF fibre with $NA = 0.14$ was used. Two cases were considered: with and without aberration correction. For the aberration correction, 1st order Zernike polynomials were programmed on the SLM (see section 2.7). It was empirically found that defocus profiles defined by $Z_{def} = C_{def} \cdot \sqrt{3} \cdot (2X_N^2 + 2Y_N^2 - 1)$ were sufficient to achieve good compensation. The condition used to conclude this was that when linearly combining defocus with other 1st order Zernike polynomials the optimized coupling was improved by less than 10%. Therefore, for simplicity the aberration correction was limited to finding the appropriate weight factor C_{def} . Figure 24 (a) shows this optimized defocus coefficient C_{def} as a function of θ_l . The fibre coupling results are shown in Figure 24 (b). Without aberration correction, the coupling loss $\mathcal{L}_F$ is higher than 10 dB for $\theta_l > 20^\circ$. Defocus compensation keeps this loss below 5 dB for the entire FOV.

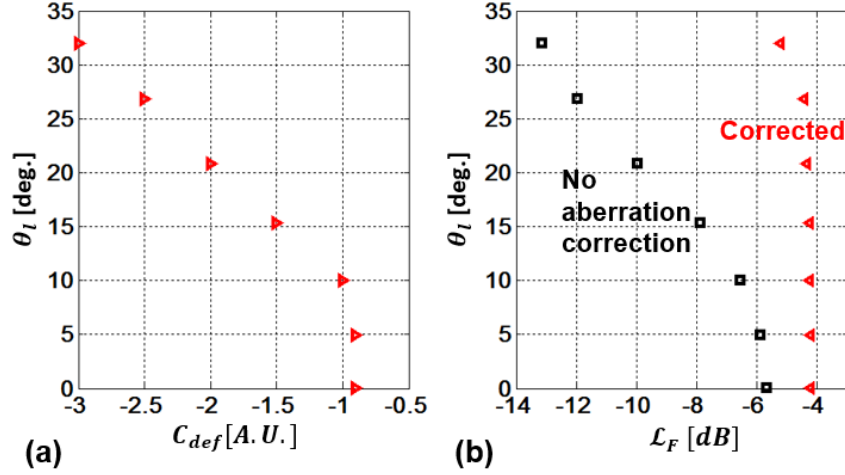


Figure 24. AM simulation results. ~~The vertical axis θ_l coincides for the three curves.~~ L_F is the fibre coupling loss and C_{def} is the defocus profile coefficient.

In these simulations only the Rx side of the link was considered. However, due to the bidirectional nature of the Tx-Rx link, a similar aberration correction needs to be applied by the SLM at the Tx side, which will shape the output beam. That is, unless this correction is applied, the transmitted narrow beam will suffer from beam spreading due to aberrations added by the Tx AM. This will be verified in the following experimental sections.

3.4 CW LINK EXPERIMENTS

A proof-of-principle experiment is carried out here using identical steering modules as shown in Figure 25. A CW laser source operating at 1550 nm is used as an input to the Tx creating a narrow beam in free space. This beam propagates over ~ 3 m and enters an Rx module. The output signal is read by a power meter. The AM modules are implemented based on the design defined in section 3.3.

This section describes the experimental characterization of this symmetric link. First, the beam divergence under free space propagation as well as the geometrical aberrations in the AM are

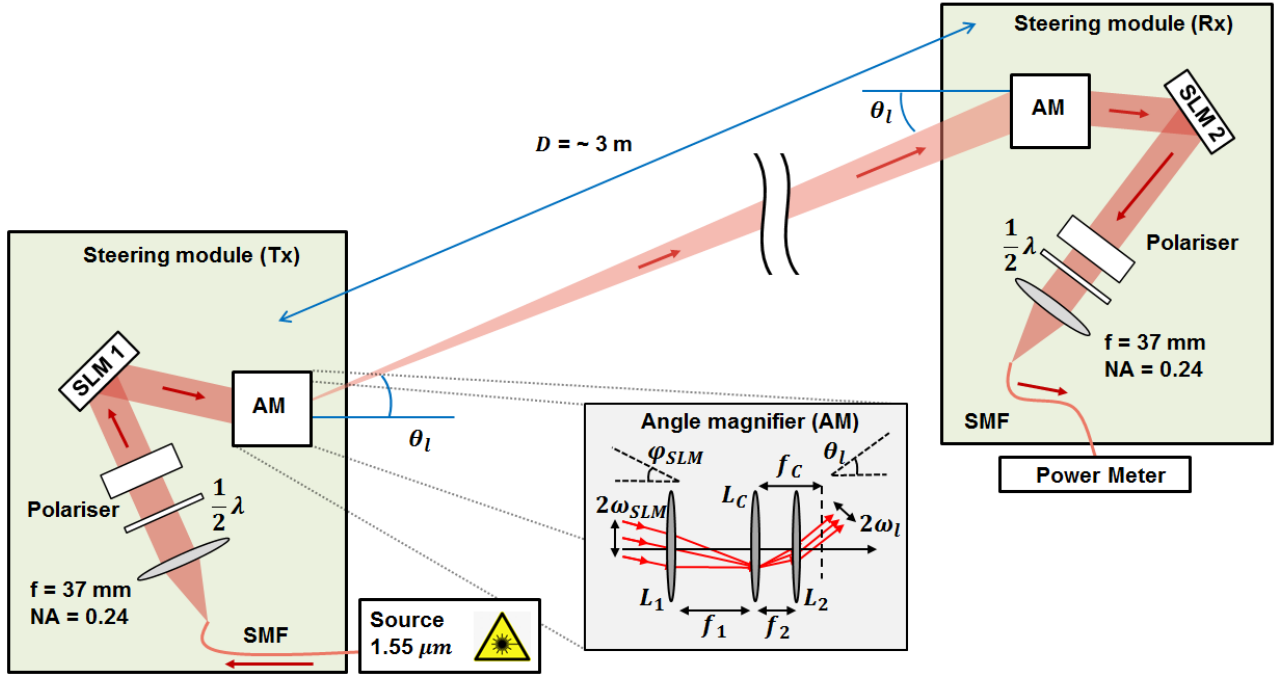


Figure 25. Symmetric link layout. The Tx and Rx modules are identical.

studied. The link FOV is then experimentally determined. Additionally, the total link loss is obtained as a function of θ_l for an optimized link operation including the steering alignment and correction for aberrations. This allowed us to estimate the link budget to perform the subsequent communications experiments. Finally, the link dispersion effects due to the SLM dependence on the wavelength of operation are studied. This is important to understand the WDM capabilities of the system.

3.4.1 Free space beam propagation

Figure 26 shows the Tx / Rx experimental layout. After the Tx AM, the beam propagates in free space and an InGaAs camera records the beam transverse profile when varying the propagation distance Z . The results are given in Figure 27 (a) for $\theta_l \sim 0^\circ$ (i.e. negligible geometrical aberrations) so that the divergence due only to diffraction can be estimated. The beam diffracts keeping an

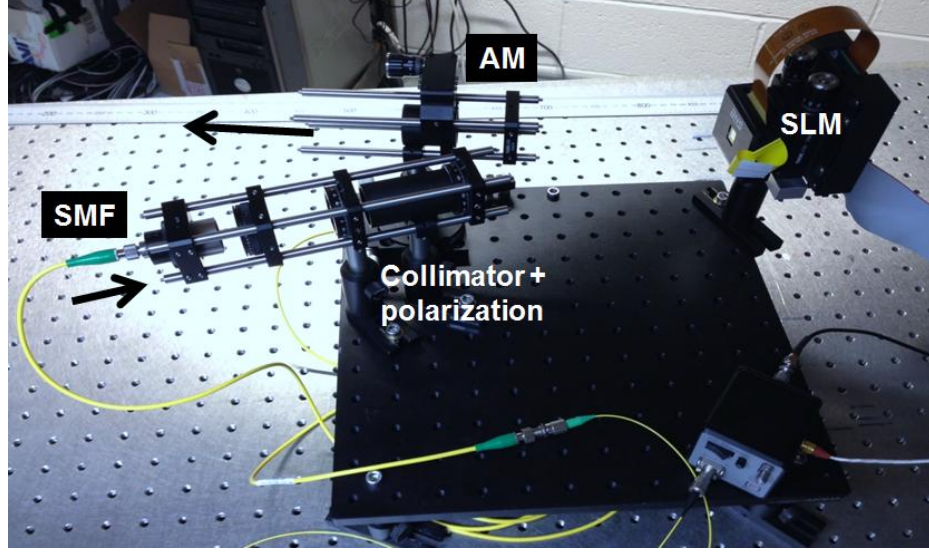


Figure 26. Experimental setup for the Tx / Rx steering module.

approximately Gaussian profile as it propagates with a measured divergence angle of $\vartheta_{div} = 0.06^\circ$.

Theoretically, the divergence from equation (16) is approximated to,

$$\vartheta_{div}^0 \sim \frac{\lambda}{\pi \omega_{Tx}}, Z \gg Z_{Tx} \quad (19)$$

Where Z_{Tx} and ω_{Tx} are the Rayleigh length and beam waist, respectively, of the Gaussian beam in free space. Using equation (17), $\omega_{Tx} = 0.55$ mm can be estimated for an AM with $\gamma = 10$ and an input beam width $\omega_0 = \omega_{SLM} \sim 7$ mm specified by the Thorlabs F810APC-1550 collimator. Then, substituting in equation (19) $\vartheta_{div}^0 = 0.05^\circ$ is obtained. This theoretical value is in agreement with the experimental $\vartheta_{div} = 0.06^\circ$, the latter being slightly higher due to either AM misalignment or small aberrations in the system.

These divergence results apply only to small link angles. For large θ_l , beam distortions in the AM are also a major factor in the spreading of the beam under propagation. This was confirmed experimentally. For $\theta_l \sim 30^\circ$ the beam spreading at $Z = 3$ m reduced coupling to a degree where

(a) $\theta_l = 0^\circ$, $C_{def} = 0$



(b) $\theta_l \sim 30^\circ$, $Z = 1\text{ m}$



Figure 27. Beam propagation study for (a) small $\theta_l \sim 0$ and variable free space distance Z and (b) large $\theta_l \sim 30^\circ$ and variable defocus correction C_{def} .

no optical power was detected at the receiver. Corrections for geometrical aberrations were then required to keep a narrow beam under propagation. Defocus phase profiles programmed on the SLM were effective, as it was predicted in section 3.3.1. For a qualitative example, Figure 27 (b) shows the beam's transverse profile for $\theta_l \sim 30^\circ$ after $Z = 1\text{ m}$ whilst varying the defocus coefficient C_{def} (see section 2.7 to understand C_{def}). It can be seen that, unless the correct profile with $C_{def} = -2.7$ is added to the SLM, the beam energy disperses.

Therefore, the Tx requires corrections for aberrations. A similar correction at the Rx is expected as this FWF link geometry is symmetric. This is also consistent with the simulations obtained in section 3.3. Figure 28 gives the defocus coefficient C_{def} as a function of θ_l for the SLM-AM steering module. The coefficient was experimentally determined by visual optimization when inspecting the beam's transverse profile using an IR camera located at $Z = 1\text{ m}$ from the Tx. The visual optimization consisted of finding C_{def} giving the smallest (least diffracted) beam profile.

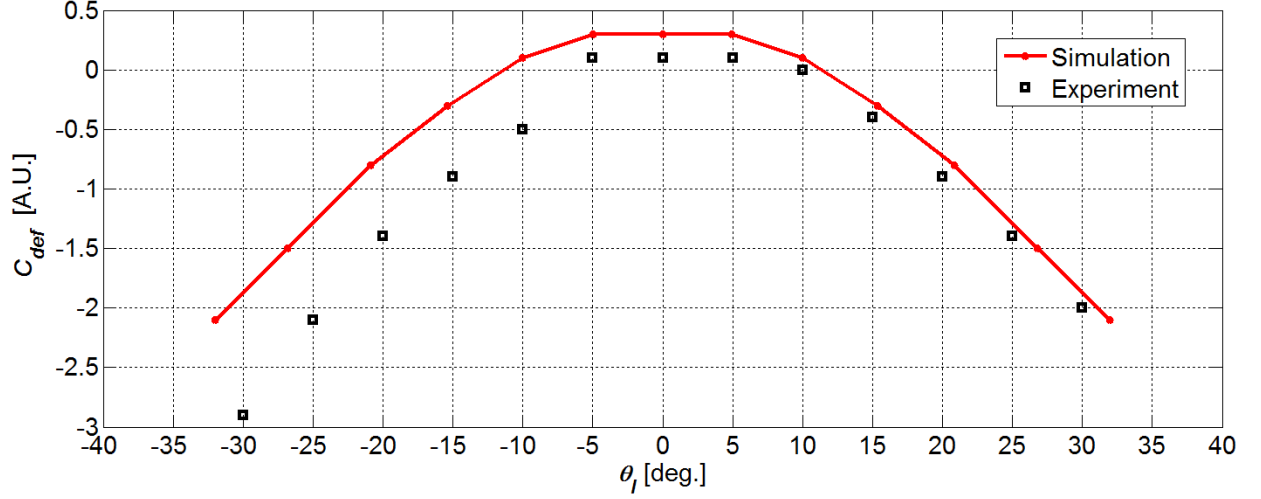


Figure 28. Tx beam correction. Defocus coefficient as a function of the link angle θ_l .

There is a similar trend for both the simulation and experimental curves: low angles require a constant defocus profile C_{def}^0 , followed by a linear C_{def} increment after $|\theta_l| \geq 5^\circ$. This initial C_{def}^0 is unique for each transceiver as it depends on the optical alignment within the AM (relative position of its lenses) and the fibre collimator. It can also be seen that a larger defocus correction is required for a negative θ_l in the experimental curve. This is due to the AM's optical axis being displaced with respect to the SLM's, thus creating some asymmetry (and uneven aberrations) in an otherwise circularly symmetric optical system. An ideal system with perfectly aligned components would present symmetric compensation for aberrations as well as $C_{def}^0 = 0$.

Finally, Figure 29 shows the experimental link angle θ_l as a function of the SLM steering θ_{SLM} . The θ_l range applies for both the Tx and Rx and it takes into account the defocus compensation for aberrations. The simulation and experimental curves coincide following an angular magnification performed by the designed AM given in Figure 21. The trend is quasi-linear. The deviation from a

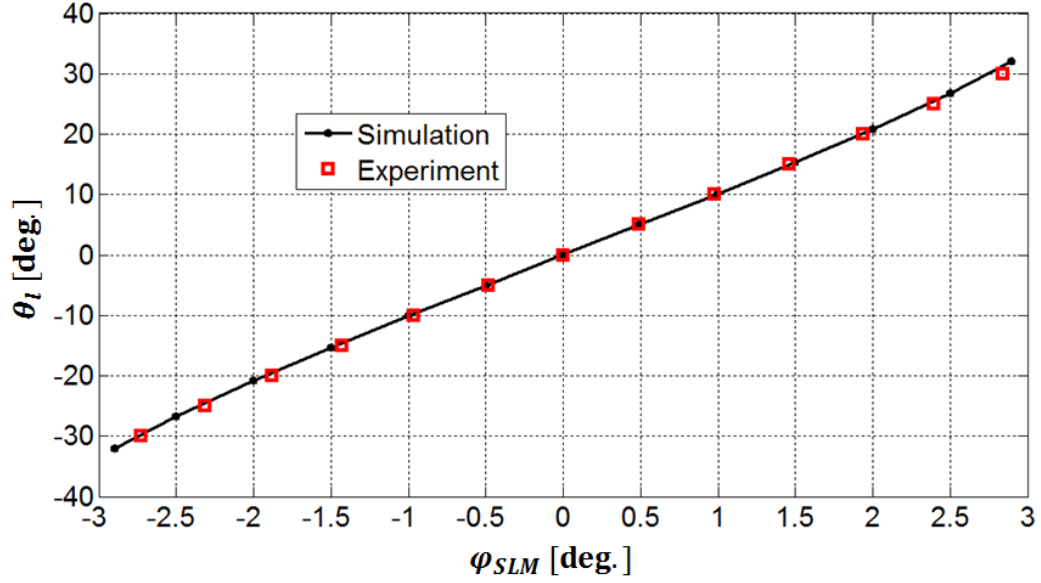


Figure 29. Link angle θ_l as a function of the SLM steering ϕ_{SLM} .

linear performance is due to the AM not having ideal thin lens components, thus the lenses' focal lengths slightly vary as a function of θ_l .

3.4.2 Optimized link loss and alignment

The individual steering modules have been experimentally characterised over the design FOV of $\theta_{FOV} = \pm 30^\circ$. The overall link performance is now considered when two identical transceivers are used at both ends of the SMF-wireless-SMF geometry as shown in Figure 25. In order to minimise losses, the Tx and Rx are first aligned for each θ_l . This is undertaken using manual control of the beamsteering function as well as the defocus coefficient C_{def} . The following procedure was used:

- 1) The Tx-Rx distance is set to $Z = 3\text{m}$ and the two units are co-aligned at $\theta_l = 0^\circ$.
- 2) The Tx beamsteering is set to the desired angle θ_l . The Tx module is then rotated so that the output beam falls approximately within the centre of the Rx aperture.

- 3) An infrared camera is used to visualize the beam footprint at an intermediate plane $Z = 1$ m. Adaptive optics (AO), in the form of a defocus phase hologram defined by C_{def} , is progressively added to the Tx SLM. The Zernike surface is modified in order to achieve the smallest beam diameter via visual optimization in the camera plane (refer to section 3.4.1).
- 4) Steps 2) and 3) are repeated for the Rx module by temporarily using it as a transmitter. The coarse alignment is completed.
- 5) The fine alignment requires a 2D search approach. The beamsteering at the Tx steering module is scanned in the vertical and horizontal directions in steps of $\delta k = 0.1^\circ$. When the maximum power coupling into the Rx is found, then AO is also refined to further improve the power coupling. This is achieved by tuning C_{def} in steps of ± 0.1 .
- 6) Step 5) is repeated at the Rx. The downlink is then properly aligned.

This procedure gave steering symmetry to the system. The transceiver's orientations were such that the beamsteering required on both units was very similar ($\pm 1^\circ$ difference). This is not a requirement for the system to work: Tx and Rx can be oriented differently so different steering angles are set on both transceivers when the link is aligned.

Once the alignment is carried out, the total link loss Γ can be estimated as a function of θ_l . Figure 30 shows the corresponding experimental results as well as the simulated loss curves for different AO implementations. Γ has the following contributing terms,

$$\Gamma(\theta_l) = \mathcal{L}_V + \mathcal{L}_F(\theta_l) + \mathcal{L}_{SLM}(\theta_l) + \mathcal{L}_O \quad (20)$$

where $\mathcal{L}_V$, $\mathcal{L}_F$ and $\mathcal{L}_{SLM}$ are the vignetting, fibre and SLM loss, respectively. $\mathcal{L}_O$ refers to other sources of loss not included here such as reflection or scattering loss from the optical components.

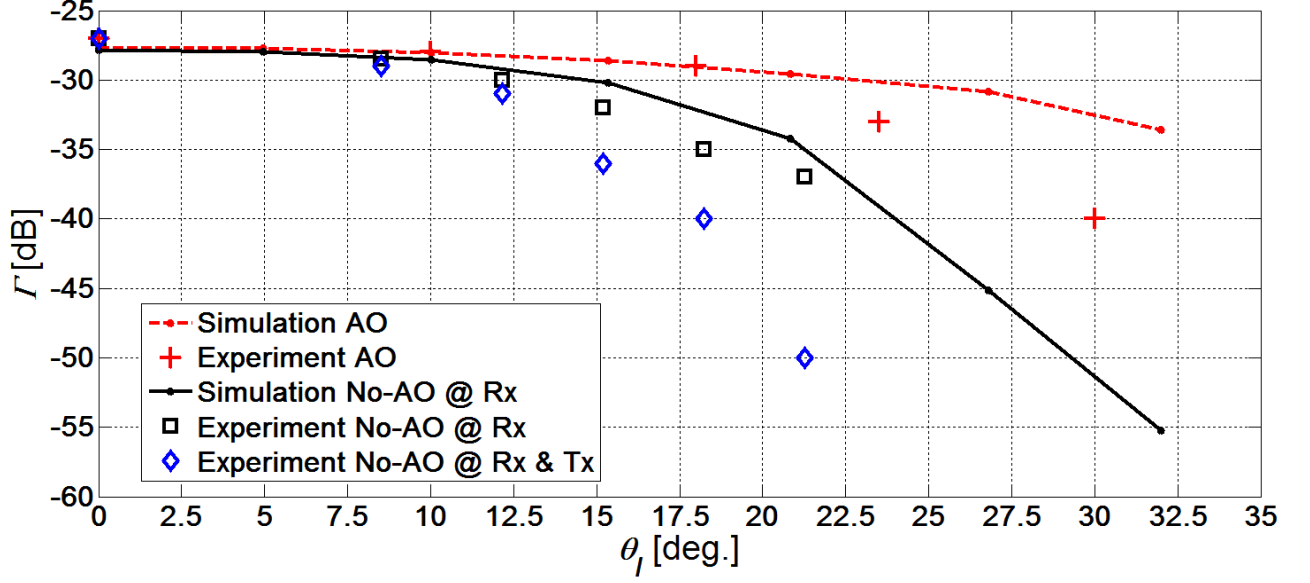


Figure 30. Link loss characterization. The experiment and simulation data are displayed for different AO scenarios.

$\mathcal{L}_V = -25$ dB is predominant loss factor, which is also independent of θ_l . $\mathcal{L}_{SLM}$ is the sinc^2 loss due to the pixelated nature of the SLM. This contributes to a maximum of 4 dB at the steering range limit (see section 2.5.3).

Comparing the experiment and simulated curves, there is a good agreement (within ± 3 dB) for $\theta_l \leq 20^\circ$. However, the simulation underestimates the link loss for $\theta_l > 20^\circ$. This is possibly due to the simplified Zemax SLM modelling as a continuous phase array. The model was not capable of including the SLM's 2π phase modulation constraint nor the inter-pixel crosstalk (see section 2.5).

Finally, the importance of AO in SMF-wireless-SMF link margin was experimentally verified. The system with no AO at the Tx nor the receiver suffers from high loss for $\theta_l > 10^\circ$. When no AO is applied to the receiver, the additional loss becomes considerable for $\theta_l > 20^\circ$. AO at both

terminals gives the best performance. This justifies the use of SLMs instead of more conventional steering devices with no AO capability.

3.4.3 Wavelength study

So far the link performance for a single wavelength channel has only been studied. Multiple channels are desirable to increase the link's aggregate data rate. Moreover, WDM capabilities allow for FWF implementations that could be compatible with the next generation of passive optical networks (NG-PONs) [26]. The SLM's dispersive effects limit the WDM capabilities of the FWF link shown in Figure 25. For the Tx, it can be shown that the beam walk-off ΔS at the Rx plane is:

$$\Delta S \sim \theta_l \cdot Z \cdot \Delta\lambda / \lambda_0 \quad (21)$$

Where $\Delta\lambda = \lambda - \lambda_0$ is the wavelength detuning with respect to the aligned link at λ_0 , Z is the distance between Tx and Rx. This displacement ΔS is important as an Rx entrance aperture of 10 mm is used defined by the lens with focal length f_2 in Figure 21. Excessive ΔS would therefore lead to increased loss.

The effect of ΔS was experimentally measured at $Z = 3\text{m}$ for an initial alignment with $\lambda_0 = 1550\text{ nm}$. The link performance is shown in Figure 31 for different curves as θ_l changes. In all cases, the link loss increases as a function of the wavelength detuning $|\Delta\lambda|$ and the rate accentuates with θ_l . This is consistent with (21).

It can be concluded that the available wavelength range to operate a WDM configuration within, e.g. the power budget line plotted, noticeably reduces as θ_l increases. Predictions on the aggregate

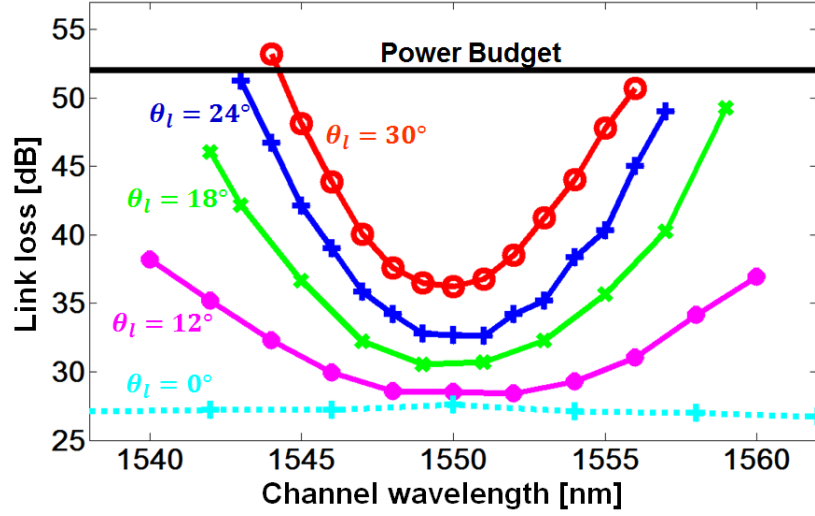


Figure 31. Link loss vs. channel wavelength. The power budget line is the power link margin for a maximum launch power of 10 dBm and a receiver sensitivity of -42 dBm. This sensitivity value is set as an example and it will be determined in the following section as part of the communications experiment.

data rate capabilities of this type of links will be studied in later sections. First, a communications experiment using WDM techniques is studied.

3.5 TRANSMISSION EXPERIMENT

The FWF link characterized in section 3.4 is transparent, i.e. independent of the data rate and modulation formats. Thus, for our optical communications experiment most fibre-based transmission systems are suitable as long as a sufficient link margin is provided. The transmitter output power is limited to 10 dBm due to eye-safety regulations. The experimental link loss is as high as ~40 dB at $\theta_l = 30^\circ$ as shown in Figure 30. Therefore, the receiver sensitivity must be better than -30 dBm at the targeted data rate.

In this section, the FWF was successfully integrated to two transmission systems given the inherent transparency of the wireless link design. Initially, an intensity modulation – direct

detection (IM-DD) link was established based on the available equipment in Oxford laboratories. Subsequently, a state-of-the-art optical digital coherent system was used as part of a research collaboration established with the Optical Network Group based in University College London.

3.5.1 Intensity modulation – direct detection experiment

IM-DD has been typically used for OWC demonstrations [18]. Receiver sensitivities as low as -38 dB (with EDFA pre-amplification) have been reported for data rates as high as 10 Gb/s [70], [71]. This sensitivity was sufficient to carry out preliminary IM-DD experiments using the FWF studied in section 3.4.

The experiment is shown in Figure 32. The transceivers were separated by a distance $\Delta z = 3\text{m}$. Infrared light from a C-band tunable source (Agilent 81642A) was modulated using an electro-absorption modulator (EAM, Corning). The EAM was driven by an On-off keying (OOK) non-return to zero pseudorandom bit stream (NRZ-PRBS) RF signal that was generated using a bit error rate test (BERT) kit (Agilent N5980A). The modulated output light was then amplified using a booster erbium doped fibre amplifier (EDFA) with a flat gain over the C-band (Keopsys KPS-BT2-C-21-BO-FA). Light from the fibre then propagated through the FWF link characterized in section 3.4.

The received light after Unit 2 was then amplified (Keopsys CEFA-C-HG-SM-40-M201) before reaching a fibre pigtailed detector (New Focus 1511). The detector RF output could either be connected to a BERT kit or a 3.5 GHz Lecroy oscilloscope. The receiver EDFA preamplifier gave an ~ 20 dB gain. The detector sensitivity was ~ -20 dBm at a bit rate of 3 Gb/s. This provided an

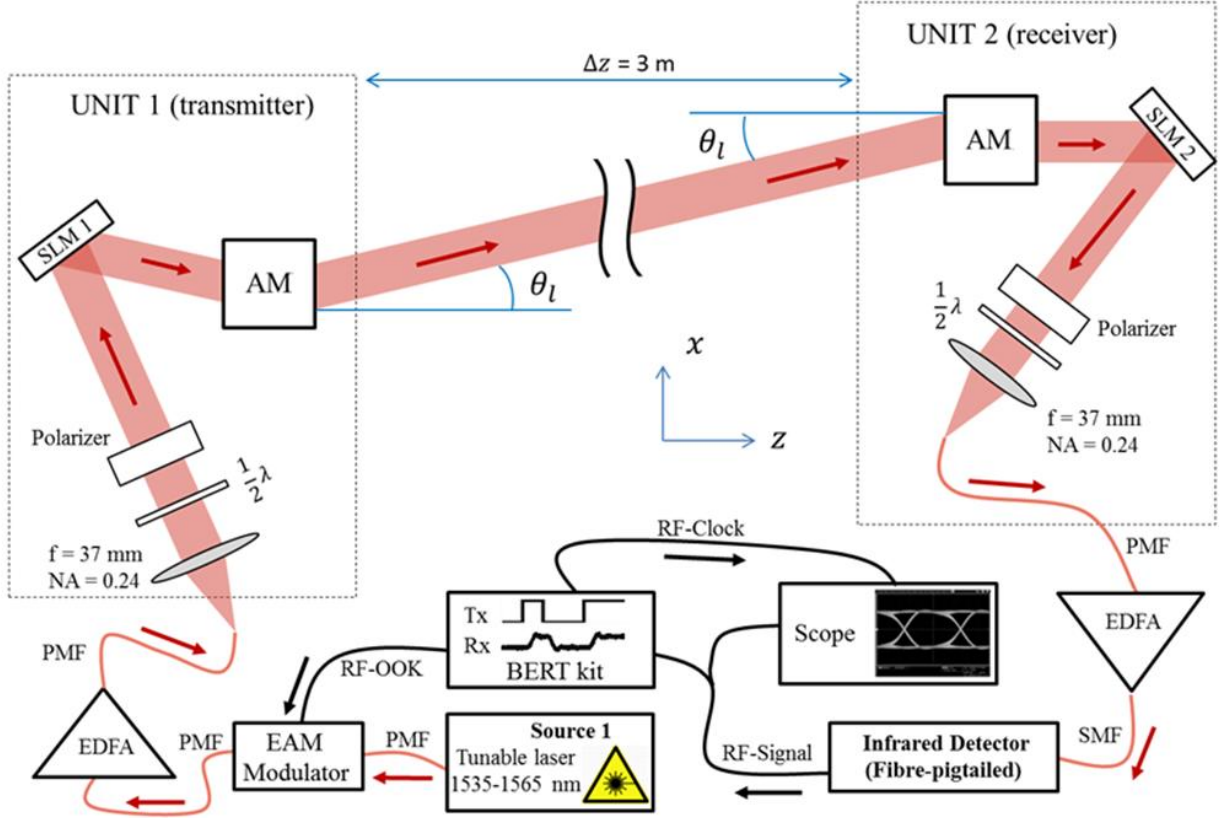


Figure 32. Experimental set-up: AM is an angle magnification module; PMF is a polarization maintaining fibre which is also SMF (Thorlabs PM1550-XP); SLM is a spatial light modulator; EDFA is an erbium doped fibre amplifier; and $1/2\lambda$ is a half wave plate retarder.

improved receiver sensitivity of ~ -40 dBm, leading to an effective link margin of ~ 50 dB considering a Unit 1 output power of $+10$ dBm.

The link angle was set to $\theta_l = 0^\circ$. The received power P_r before the optical pre-amplification was then $P_r \sim 2 \mu\text{W}$ (-27 dBm). For this P_r , the OOK 3.125 Gb/s data-transmission experiment gave an error-free link (eye diagram shown in Figure 33 (a)).

The link angle θ_l was then set to $\theta_l = 32^\circ \pm 1^\circ$ resulting in a received power of $P_r \sim 0.6 \mu\text{W}$ (-32.2 dBm). The corresponding eye diagram is shown in Figure 33 (b) with a measured BER of

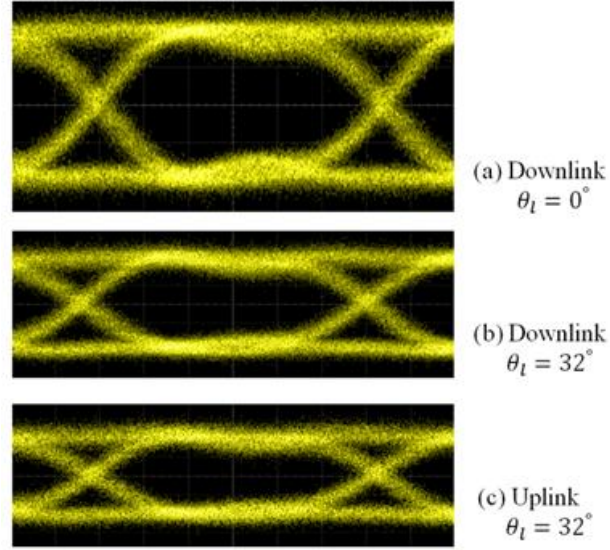


Figure 33. Eye diagrams at 3.125 Gb/s. Pictures (a), (b) and (c) are properly scaled with one another.

10^{-9} . The link's bidirectional operation was then tested. The uplink was operated by interchanging the input and output optical fibres connected to the transceiver's Unit 1 and 2. Unit 2 thus becomes the transmitter and Unit 1 the receiver. The coupled optical power was $P_r \sim 0.5 \mu\text{W}$ (-33 dBm). The measured BER was 10^{-8} . The open eye diagram is shown in Figure 33. The IM-DD data rates were limited by the transmission system rather than the FWF link loss. Therefore, a collaboration with the Optical Network Group (ONG) at University College London (UCL) was initiated to further test the FWF capabilities using a state-of-the-art coherent transmission system. The FWF link was installed in the ONG lab facilities in London. Joint experiments were undertaken to demonstrate wide area coverage OWC at data rates higher than 100 Gb/s.

3.5.2 Coherent WDM experiment

For fibre-based coherent systems, Terabit wireless data rates have been demonstrated (Chapter 1 Figure 2). Receiver sensitivities better than -40 dBm are possible with complex phase and amplitude modulations at data rates of 10s of Gb/s [72]. This section describes the performance of the UCL coherent transmission system when combined with the FWF link characterized in section 3.4.

The FWF link was connected via SMF fibres to an optical digital coherent system as shown in Figure 34. The coherent transmitter is a Nyquist-WDM (N-WDM) transceiver [73] that generates up to 14 WDM channels. Each channel carried 8Gbaud X-QAM ($X = \{4, 16, 64\}$) signals with a channel spacing of ~ 8.2 GHz. The data rate per channel varies depending on the modulation scheme: 4, 16 and 64 QAM gave a useful data rate of 14.88, 29.9 and 44.85 Gb/s, respectively including a 7% loss in capacity due to FEC overhead.

The resulting N-WDM signal from the coherent transmitter is amplified using a booster EDFA. Subsequently, a variable optical attenuator (VOA) is used to further control the output power level. This modulated optical signal is connected via an SMF fibre into a Tx steering module, which

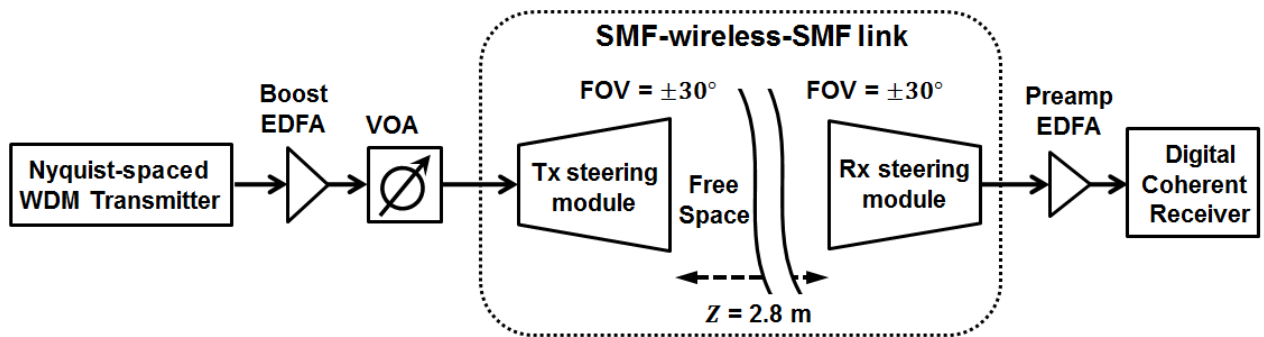


Figure 34. Experimental setup. The transmission system is an extension of the SMF-wireless-SMF link. VOA is a variable optical attenuator.

steers the light through free space to the Rx steering module. The free-space link control and alignment is carried out as described in section 3.4.2. The Rx module couples the signal back into the Rx's SMF input fibre and optically pre-amplified using an EDFA to improve the receiver sensitivity. A standard coherent receiver with an electrical bandwidth of 63GHz is used to process the N-WDM channels simultaneously [73]. Data is recorded using a 160 GSample/s real-time oscilloscopes. Digital signal processing (DSP) is applied subsequently on the captured waveforms to recover the Nyquist pulse shaped X-QAM signal [73].

For the WDM experiment either 7 or 14 N-WDM channel combs were used with the corresponding optical spectra given in Figure 35 (a) and (b), respectively. For both spectral combs, the channels' peak powers were always above -20 dBm, i.e. 7 and 14 channels in Figure 35 (a) and (b), respectively. This homogenized the WDM performance per channel as the combs were flat (within ± 1 dB relative peak power). The remaining formed sidebands with peak powers below -20 dBm were ignored although they represented an unwanted power loss.

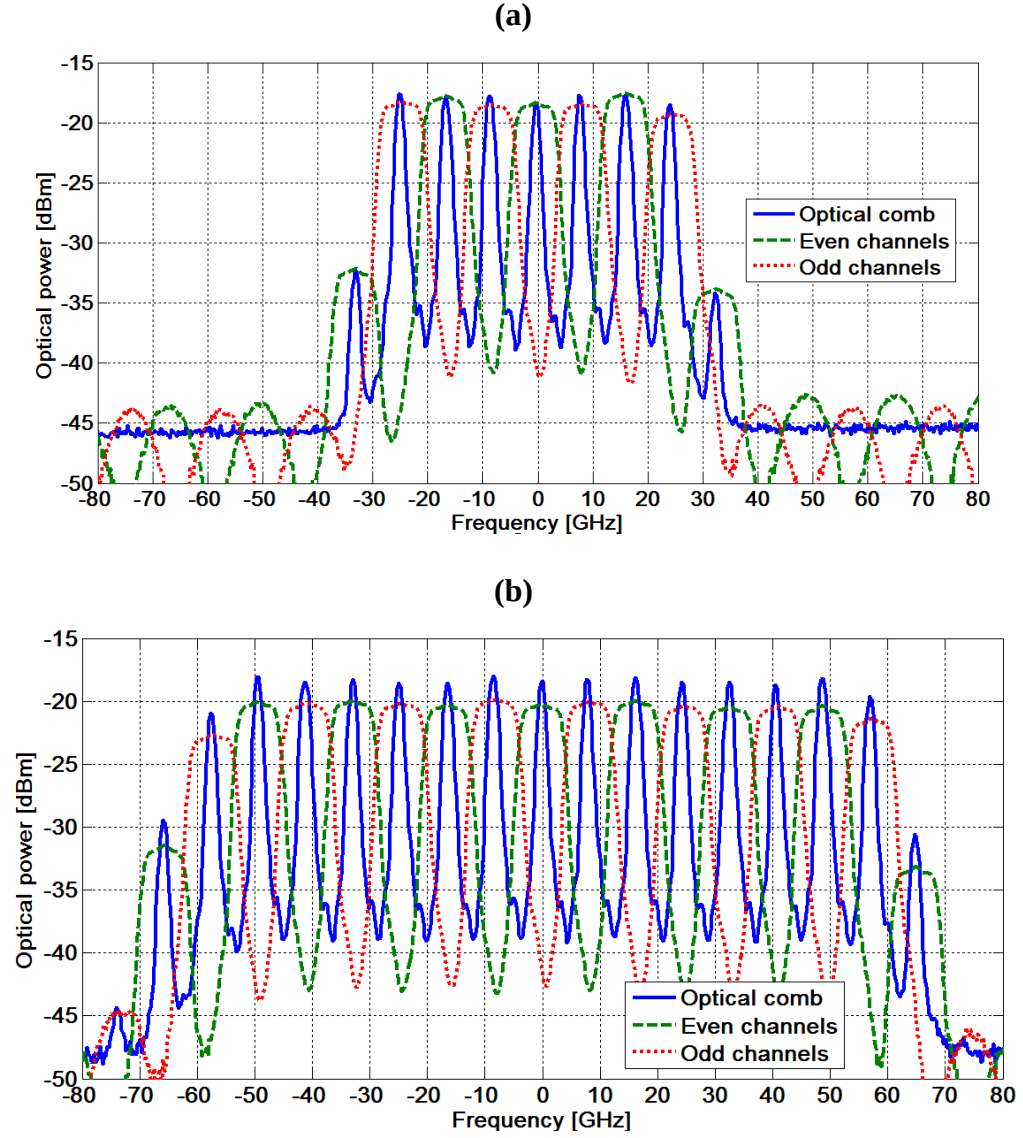


Figure 35. Measured optical spectra at the transmitter for (a) 7 and (b) 15, N-WDM optical comb (solid line) with a resolution of 0.01nm. The even and odd carriers are separately modulated. The modulated carriers are also plotted for a 16-QAM symbol (dash and dotted lines).

3.5.3 Receiver sensitivity

Back-to-Back (BtoB) experiments were carried out to characterize the receiver sensitivity as function of the Rx input power. This power is measured just before the EDFA preamplifier (see Figure 34). The results are shown in Figure 36 for different QAM constellations. As the modulation changes from 4QAM to 16-QAM and 64 QAM, there is a sensitivity penalty of ~ 8 and ~ 18 dB, respectively. This relative drop for the 16QAM is as predicted by the theoretical curves. However, the 64-QAM modulation suffered from additional penalties not explained by the theory but related to other unforeseen impairments. Overall, changing from 4QAM to 16-QAM and 64 QAM gave a bits per-symbol enhancement of 2 and 4 bits, respectively.

The receiver sensitivity as a function of θ_l was also studied. For this experiment, a modified coherent system to the one described in section 3.5.2 was implemented. It used a 10-Gbaud 16-QAM channel with 10.1GHz channel spacing [74]. However, the FWF link was the same as the one shown in Figure 34. Figure 37 shows a plot of BER vs Rx input power (measured just before

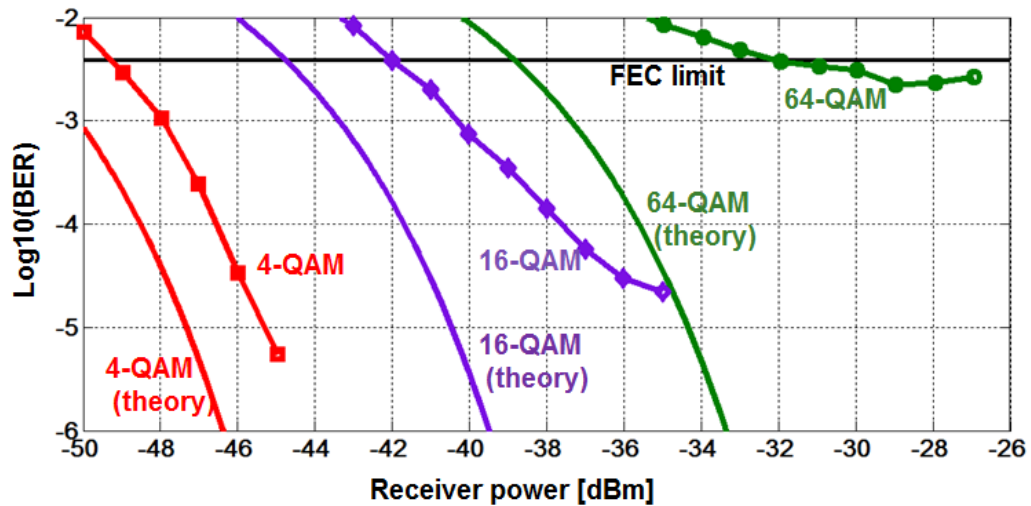


Figure 36. Sensitivity curves for different X-QAM modulations. The theoretical curves were taken from [72].

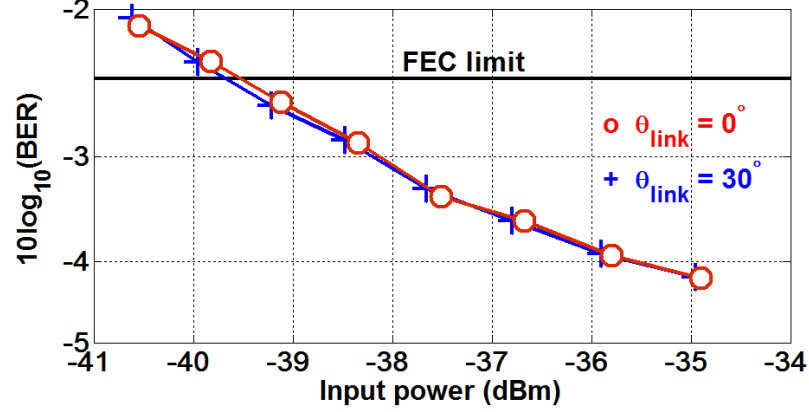


Figure 37. Receiver sensitivity. The modulation format is 16-QAM and the symbol rate is 10 Gbaud. The plotted curves are given for different link angles θ_l .

the receiver EDFA preamplifier shown in Figure 34) for two different link angles $\theta_l = 0^\circ$ and $\theta_l = 30^\circ$. The VOA attenuation was set 12 dB higher for $\theta_l = 0^\circ$. It can be seen that the resulting curves overlap, which demonstrates that the increasing θ_l only affects the link loss and causes no other impairments. Therefore, the FWF link can be modelled as a variable loss module embedded in the coherent system.

3.5.4 Throughput study

The system BER performance was studied as a function of the FWF link loss for different modulation formats and N-WDM configurations. Figure 38 shows the BER vs attenuation of the VOA. The link operates correctly if a BER is lower than the limit that can be corrected using an FEC code, and this line is also marked on the graph. The intersection of the FEC limit with each BER curve indicates the available link margin for that configuration. (As an example, for the “1-ch $\theta_l = 30^\circ$ 4 QAM” link it shows that an additional 22 dB of attenuation can be added and the BER remains within acceptable limits).

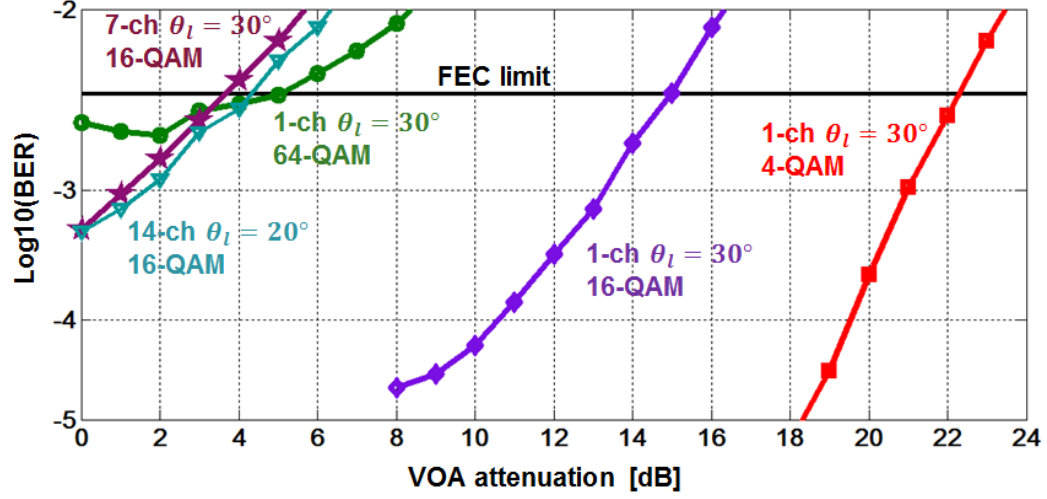


Figure 38. Coherent system performance. The plotted curves are defined by the link angle θ_l , the modulation format and the number of transmitted N-WDM channels.

Therefore, an error-free FWF link is demonstrated over ~3 m range at 418 Gb/s (14 x 29.9 Gb/s) and 209 Gb/s (7 x 29.9 Gb/s) with a wide FOV (full-cone) of 40° and 60° , respectively. To the best of our knowledge, this is the fastest demonstration of a wireless link with a FOV that offers practical room-scale coverage.

The bidirectional capability of the FWF link was also tested using a similar coherent system to that used in the previous 400 Gb/s experiment. Here a 10-Gbaud 16-QAM channel with 10.1GHz channel spacing was used [74]. The results are given in Figure 39. The downlink was the initial direction in which the mechanical alignment was carried. The uplink curve was obtained by interchanging transmitter and receiver fibres without altering the alignment of the system. It can be seen that there is no variation in the performance as the link direction is changed. Additionally, a heat gun was used to disturb the free space between transceivers where the infrared narrow beam was propagating. This potentially induced changes in optical path's refractive index. In doing so, no fluctuation in the system performance was seen. The measured robustness may be due to the

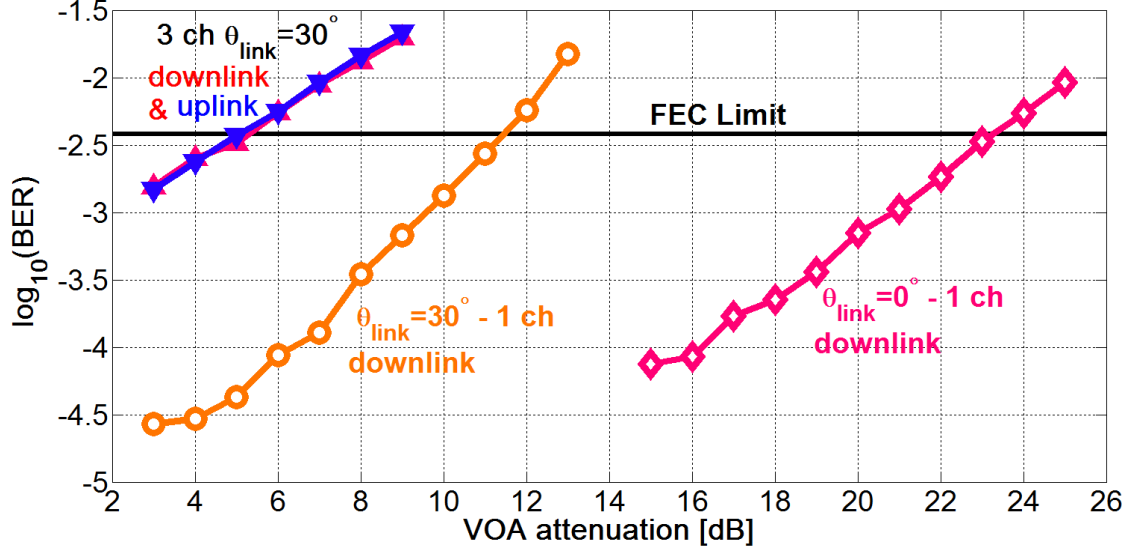


Figure 39. Coherent system performance. The plotted curves are defined by the link angle θ_l , the modulation format and the number of transmitted N-WDM channels.

weak effect of turbulence for short indoor links. This is a promising indication that such schemes are suitable for indoor environments with relative turbulence, although more quantitative tests are needed.

3.6 TOWARDS TERABIT/S DATA RATES

The aggregate data rate could have been increased based on the available link margins shown in Figure 38. However, in the previous experiment the WDM comb was limited to 14 channels. At the same time, changing the modulation format from 16-QAM to 64-QAM produced a strong power penalty of ~ 10 dB at the FEC limit. Moreover, there is a strong BER saturation present in the “1ch $\theta_l = 30^\circ$ 64-QAM” curve as shown in Figure 38, which translates into no relative BER improvement as the received optical power increases. Thus, the coherent system impairments (and not the available link budget) limited the link throughput.

Assuming a loss limited WDM transmission system, then a theoretical throughput as a function of θ_l can be estimated using CW link margins and loss arguments only. The following steps were followed:

- 1) The overall link margin was set to 52 dB considering a 16 QAM modulation with experimental sensitivity of -42 dBm (see Figure 36) and a total free space beam power of 10 dBm (eye safe limit). An N-WDM setup with $N_{ch} \geq 2$ channels was assumed. The WDM comb is centred at $\lambda_0 = 1550$ nm with a channel spacing of 0.07 nm.
- 2) The WDM loss penalty due to the SLM dispersion was taken from the experiments shown in Figure 31. Each channel in the WDM comb will suffer a different penalty as a function of the wavelength detuning $|\Delta\lambda|$ with respect to $\lambda_0 = 1550$ nm.
- 3) The total power of the N_{ch} WDM comb was kept at 10 dBm to comply with eye safety limitations. Assuming equal power splitting over all the N_{ch} channels, a relative power penalty of $\log_{10} N_{ch}$ per channel was considered compared to a single wavelength beam.
- 4) The overall loss penalty is a combination of the effects described in 2) and 3). The number of N_{ch} was increased until the link margin was reached by any of the comb's channels. This was carried out for each link angle θ_l .

The estimated aggregate data rate as a function of the link angle θ_l is given in Figure 40. It shows a maximum of ~ 0.8 Tb/s at 30° and ~ 2.5 Tb/s at 18° for a loss limited transmission system where inter-channel cross-talk and other WDM impairments are neglected. It was also found that the power splitting penalty described in 3) was the predominant loss factor due to the relatively low spatial dispersion of an N-WDM comb with 0.07 nm channel separation (see section 3.4.3).

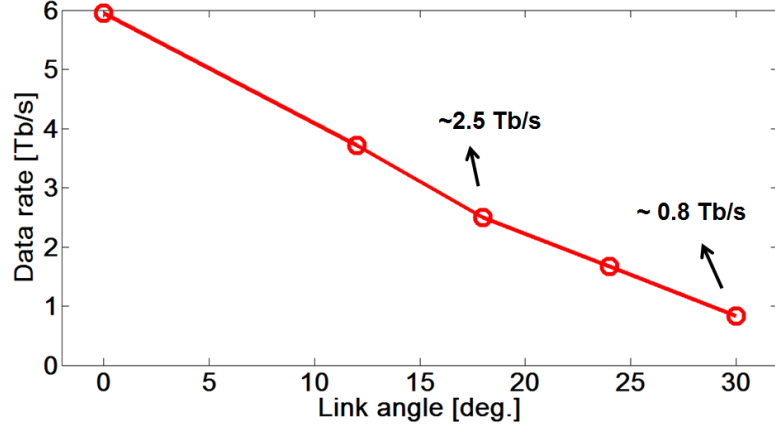


Figure 40. Theoretical throughput limit for a FWF link with a FOV = $\pm 30^\circ$.

3.7 FUTURE IMPLEMENTATIONS

A transparent FWF link with SMF-based transceivers was previously studied and a steering module was built using an SLM followed by an angular magnifier. In this section, FWF implementations using multi-mode fibres (MMF) are considered. A generalized steering system with a cost effective design is also proposed.

3.7.1 SMF vs MMF

MMFs have a larger core and higher numerical aperture than SMF fibres. The use of MMF in the transceivers studied so far, can then potentially relax the alignment and adaptive optics requirements. Two representative fibres were chosen to provide a preliminary experimental comparison: a single mode fibre (SMF-9/125) and multi-mode fibre (MMF-62.5/125). This change was applied only to the Rx. The Tx was kept with the original SMF fibre.

The metric was based on the optimal fibre coupling, which is a function not only of the beamsteering but also of the defocus compensation as previously demonstrated in this chapter. The combination of steering and defocus is critical at large steering angles. Therefore, $\theta_l \sim 30^\circ$ was

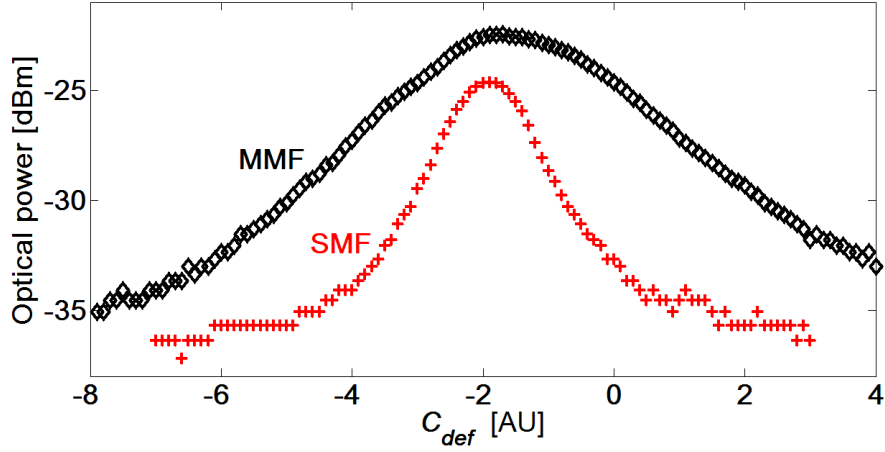


Figure 41. Experimental fibre coupling as a function of the horizontal and vertical steering angles around $\theta_l = 30^\circ$ for (a) and SMF and (b) an MMF fibre.

chosen to clearly show the difference between the two fibre types. The optimal experimental defocus coefficient was found to be $C_{def} \sim -2$ for both fibre types as shown in Figure 41. However, the SMF-based receiver is more sensitive to this parameter: a 10 dB coupling loss occurs if no defocus correction is applied.

Additionally, after fixing the optimal defocus, Figure 42 shows the experimental Rx power coupling as a function of the SLM's steering for a 2D scan around $\theta_l = 30^\circ$. The SMF fibre required a beamsteering accuracy better than $\sim 0.1^\circ$ to keep alignment loss below 3 dB as opposed to $\sim 1^\circ$ in the MMF configuration.

It can be concluded that the use of MMF fibres relaxes both the steering accuracy and the need for aberration correction. In fact, MMFs have already been proposed in the context of radio-over-fibre [75], [76] as many buildings have pre-installed MMF networks [77]. Additionally, in-premises (distances of up to 300 m) installed optical fibres networks are dominated by MMF [78].

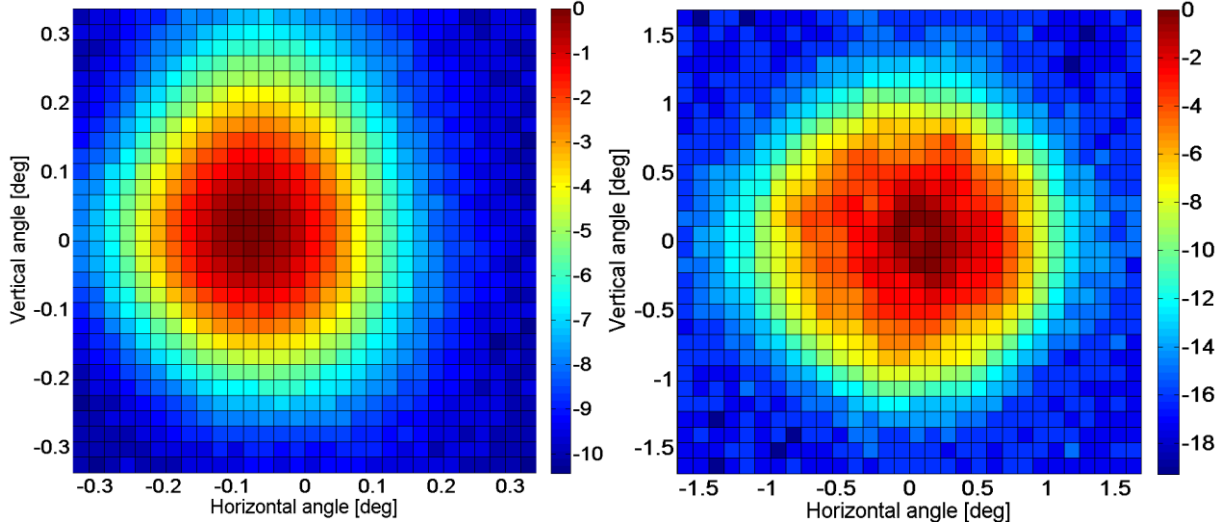


Figure 42. Fibre coupling characterization. The optical power is shown as a function of the horizontal and vertical steering angles around $\theta_l = 30^\circ$ for (a) SMF and (b) an MMF fibre. The color scale is given in dB.

3.7.2 Generalized steering system

So far a wide coverage FWF link was designed and tested based on an SLM-AM setup to achieve a practical FOV. In this setup, the SLM was used as a fine-steering module with some adaptive optics capabilities. However, this is a relatively complex device where only defocus profiles are being used for adaptive optics. Moreover, the SLM-AM architecture suffers from 25 dB or higher losses, considerably reducing the link budget as shown in section 3.4.2.

To overcome this, a generalized steering architecture is proposed in Figure 43. It combines the accuracy of small steering range devices with the discrete nature of large FOV steering components [49]. First, a collimated fibre source is deflected using an accurate steering device followed by a varifocal component. The varifocal component performs the adaptive optics function in the simplified form of defocus. The corrected and steered light is magnified using an AM to be later coarsely steered using a secondary device with discrete steering steps.

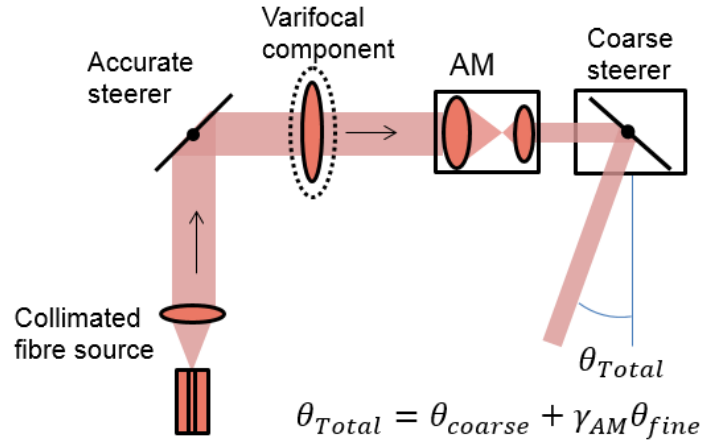


Figure 43. Generalized steering system. The accurate and coarse steerers give beamsteering angles θ_{fine} and θ_{coarse} , respectively. The AM has an angle magnification of γ_{AM} .

The advantage of using a coarse steerer is that the AM magnification can be relaxed to cover only the angular gap between discrete steps. In turn, this reduces the geometrical aberrations in the system to the point where the adaptive optics could altogether be removed or further simplified. The accurate steerer can be realized using of a fast steering mirror. The varifocal component can use a variable focal length lens. These two functionalities can also be merged in integrated components such as varifocal MEMs [79].

Chapter 4

Localization and Tracking System

4.1 OVERVIEW

FWF indoor systems require a precise alignment to establish an error free communications link. Using SMF-based transceivers, the link studied in Chapter 3 needed a steering accuracy of 0.1° to keep the fibre coupling loss below 3 dB. Additionally, the transceiver apertures at the AM module entrance are 10 mm in diameter. Thus, the narrow beam footprint exiting the transmitter has to be accurately pointed at the receiver. For the targeted 3 m free space link, this is equivalent to fractions of a degree pointing accuracy. So far, this problem has been addressed by applying manual alignment between transceivers.

However, a real implementation for indoor applications would require an automated localization and tracking system. Recalling the application scenario from the introduction (see Figure 1), the problem is complex because not only the BS needs to know the NTs locations but also the other way round. This is due to the presence of independent steering modules at both ends of the links. The overall localization and tracking system requirements can then be summarised as follows:

1. The BS has to locate several NT apertures with mm accuracy, in a generalized point-to-multipoint architecture with several NTs.
2. Each NT has to know the relative location of the BS with similar mm accuracy.
3. Precise tracking systems at both ends of the link are necessary to be able to achieve steering accuracies of 0.1° .

Indoor localization systems can address this problem using position sensing at the terminals. Several algorithms such as time-of-flight (TOF), angle-of-arrival (AOA) and relative signal strength (RSS) have proven effective [80]. These have been implemented using a variety of wireless signals spanning across the electromagnetic spectrum. Ultrasound, radio-frequency and Infrared (IR) positioning systems are among popular technologies [81]. Even visible light- based indoor localization (as part of a building lighting infrastructure) has recently shown promising results [82]. However, the localization accuracy using most of these technologies is insufficient for the FWF link requirements. As an exception to this are IR positioning systems. These use multiple imaging cameras and IR beacons to achieve the required mm precision, albeit at a relatively high cost [81].

In this chapter, a cost effective solution is presented. This solution uses a wide FOV CMOS camera at the BS and IR beacons close to the NT apertures. The CMOS camera allows for several NTs to be located and tracked simultaneously. A 2.5 mm accuracy at BS-NT distance of 3 m is achieved. This corresponds to an AOA estimation with 0.05° precision. Once the BS locates the NTs and sends the downlink beam, then the NTs are able to track the received communications beams for self-alignment. This simplifies the NTs search for the BS.

An alternative symmetric approach could have also been pursued with CMOS cameras and IR beacons at both the NT and BS terminals. The asymmetric approach was chosen to test both systems: the BS CMOS camera localization and the NT tracking of the communications beam. Finally, the overall system (BS camera based localization and NT Quad-tracking) was tested using a coherent transmission setup achieving 50 Gb/s.

4.2 GENERAL SYSTEM DESIGN

The system architecture is shown in Figure 44. The SMF-wireless-SMF link geometry and light path have already been described in previous chapters. Only the added modules to perform the localization and tracking are discussed at this point.

For the system to operate the BS has to know the location of the NTs (and vice versa). The communications link is implemented using narrow optical beams, so acquisition and tracking

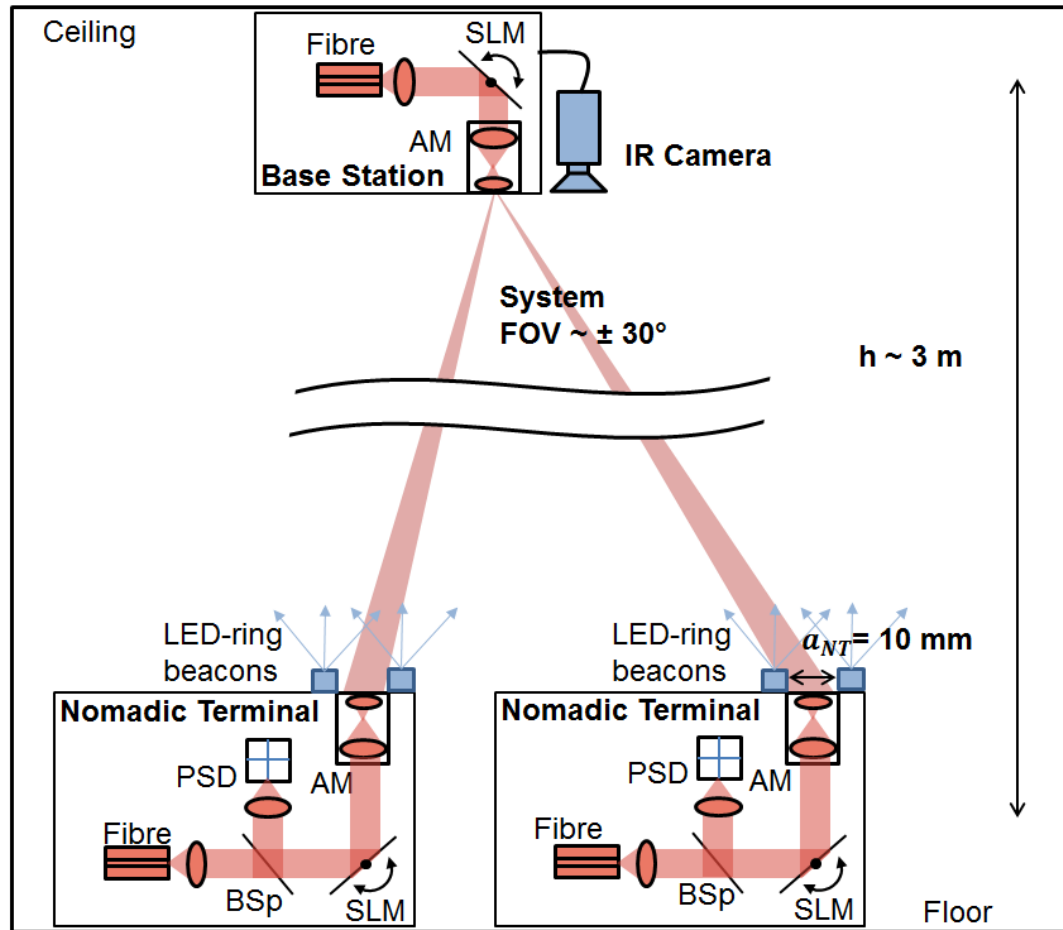


Figure 44. Architecture for the localization and tracking system. The base station interacts with 2 nomadic terminals. AM is an angular magnification module, BS is a beamsplitter and PSD is a position sensing detector.

using only this beam would be lengthy and impractical. For this reason, a beacon-based approach is used. This subsystem uses a wide FOV CMOS camera at the BS to detect the emission from a near-IR LED-ring beacon placed around the NT apertures (see Figure 44). The use of a camera allows multiple NTs to be located simultaneously, which enables a point-to-multipoint future implementation. The downlink beams are then steered using the BS SLM such that the beams enter the 10 mm NT apertures. Within each NT, a beamsplitter (BSp) takes a fraction of the communications beam (at 1550nm) to a position sensing detector (PSD). A closed-loop algorithm then uses the reading from the PSD and the NT beamsteering capability to align the beam to the receiving fibre axis. The downlinks can then be successfully established. At the same time, the uplinks are automatically aligned due to the reversibility of light and the use of narrow beam links. This bidirectional property has been demonstrated in section 3.5. This property holds if the uplink's wavelength of operation is close to that of the downlink as studied in section 3.4.3 due to the SLM steering dependence on the wavelength of operation.

In this chapter, the design and implementation of a single downlink beam is studied. The point-to-multipoint capability of the BS will be addressed in Chapter 5. In the following sections, the designs of the BS localization and NT tracking systems are given.

4.3 IR BEACON LOCALIZATION SYSTEM

From the symmetric FWF link studied in Chapter 3 the receiver's collection aperture diameter is $a_{NT} = 10$ mm and the free space narrow beam has a footprint diameter of ~ 10 mm at a BS-NT distance of 3 m. This small aperture and narrow beam combination determines the BS required steering accuracy. Figure 45 (a) shows the experimental NT coupled power vs. BS steering angle for an SMF-wireless-SMF link. It can be deduced that a steering accuracy of 0.1° is needed to

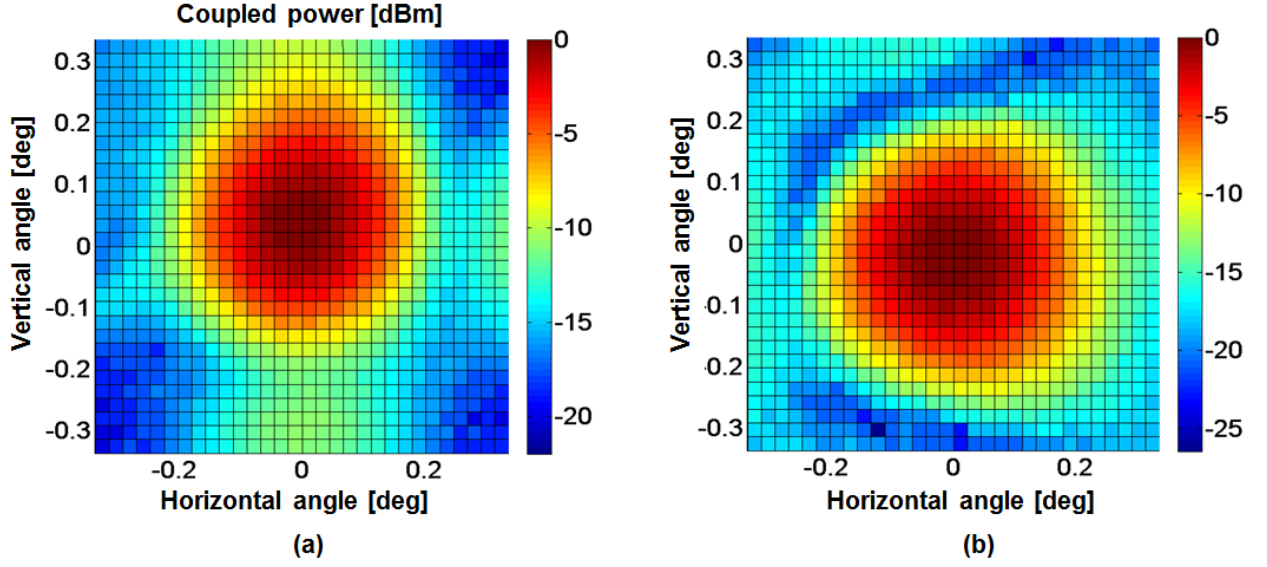


Figure 45. Experimental coupling characterization of an SMF fibre. Normalized received power as a function of (a) BS beamsteering keeping the NT fixed and (b) NT beamsteering keeping the BS fixed. The BS and NT distance is $Z \sim 3$ metres. The color scale is given in dB.

achieve a coupling loss under 3dB. This translates into a pointing accuracy of ~ 5 mm at a BS-NT distance of 3 m. In the next section, a beacon design to meet these requirements is described.

4.3.1 Beacon design

Near-IR beacons are placed at the NT such that the CMOS camera finds the centre of the NT aperture. In a circular beacon-based array, any number of beacons bigger than 3 can define its centre unambiguously. Thus, A 12-LED ring array was designed to circle the NT aperture with a diameter of $\phi_{LED} = 50$ mm. The bigger ϕ_{LED} , the easier it is to image the LED ring in the camera sensor. However, it was decided that $\phi_{LED} = 50$ mm was a good compromise between LED -ring size and resolution on the camera. Each LED (OPTEK OP291A) has an emission angle of $\pm 50^\circ$ which is sufficient for the system design FOV of $\pm 30^\circ$. The LED emission wavelength was chosen

to be 890 nm. This emission is outside the visible spectrum (thus reducing interference from lighting and sunlight), but still within the inexpensive silicon-based sensor absorption curve [83]. Figure 46 (a) shows an LED ring prototype built with these specifications. The arrangement allows the BS to estimate not only the aperture position but also the distance to the NT. In operation, an ellipsoid image of the beacon ring is captured by the IR camera, and software (MATLAB) is used to fit an ellipse to this. Figure 46 (b) gives two examples. The first one is a particular case where the NT aperture is directly facing the IR camera, thus the array is circular. The second is a more general case where the image is a projection of the circular LED array, i.e. an ellipse. The centre of the ellipse gives the location of the NT aperture and the ellipsoid major axis can be used to calculate the BS-NT distance d_{NT} . This calculation is based on geometric arguments for a camera where the imaging lens' focal length $f_{CAM} \ll d_{NT}$. The following relationship follows:

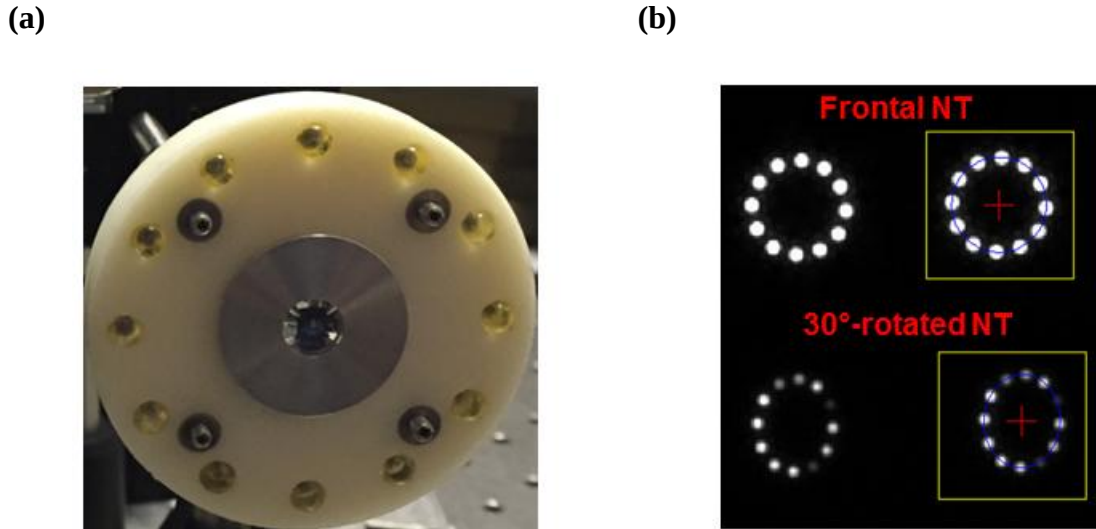


Figure 46. LED array design (a) picture of the physical module and (b) image of the LED emission captured by an infrared camera.

$$d_{NT} = \frac{\phi_{LED}}{\phi_{CAM}} \cdot f_{CAM} ; d_{NT} \gg f_{CAM} \quad (22)$$

Where ϕ_{CAM} is major axis of the ellipse in the camera sensor plane.

The choice of a high resolution camera with a low distortion imaging lens is crucial to accurately determine the ellipse in the sensor plane. The next section describes a suitable option for our system.

4.3.2 BS imaging system design

Figure 47 shows a schematic of the BS localization system. The IR camera is required to resolve the LED ring at a distance of up to 3 metres. A combination of geometric optics and diffraction arguments can be used to derive the following relationships between the object and image planes [84]:

$$\begin{aligned} \phi_{CAM} &= M_{CAM} \cdot \phi_{LED} = \frac{f_{CAM}}{d_{NT}} \cdot \phi_{LED} \\ \Delta r &= 1.22 \cdot \frac{\lambda_{LED}}{NA} = 2.44 \cdot \lambda_{LED} \cdot F_{\#} \end{aligned} \quad (23)$$

Where M_{CAM} is the system magnification, λ_{LED} is the LED wavelength of operation and NA and $F_{\#}$ are the imaging lens' numerical aperture and F number, respectively. Δr is the diameter of the each individual LED in the camera sensor plane assuming they are point sources at infinity, i.e. the diffraction limit of the optical system [84]. Evaluating equation (23) for test values $d_{NT} = 3$ m, $f_{CAM} = 3.5$ mm, $F_{\#} = 2.4$, $\lambda_{LED} = 890$ nm and $\phi_{LED} = 50$ mm, gives $\Delta r \sim 5$ μ m and $\phi_{CAM} \sim 58$ μ m. A sensor with a pixel size $p_{CAM} < \Delta r = 5$ μ m is therefore desirable.

In addition to this, the imaging system must have a FOV $> 30^\circ$. Thus, off-axis aberrations need to be minimized and a low distortion imager is required. To achieve this, an Edmund Optics CMOS

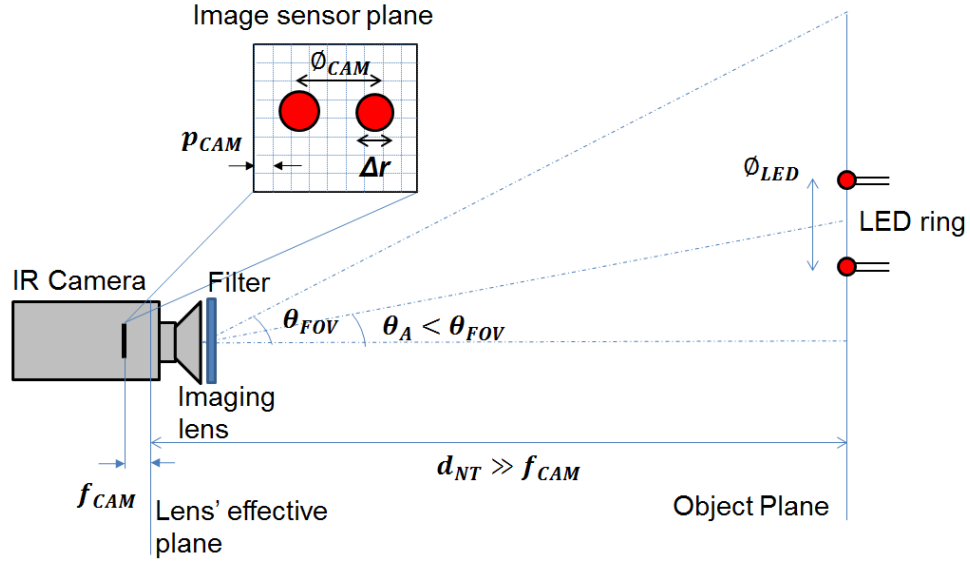


Figure 47. Schematic of the near IR imaging system.

camera (EO10012M) with a low distortion lens with $f_{CAM} = 3.5$ mm and a FOV $> \pm 40^\circ$ was combined with a $\frac{1}{2}$ inch sensor with $p_{CAM} = 1.6$ μm . This gives a resolution below the calculated diffraction limit of $\Delta r \sim 5$ μm to image each LED in the camera plane. A high-pass optical absorption filter with cut-off frequency at ~ 800 nm was also used in front of the CMOS camera to filter the ambient light.

4.3.3 System calibration

The CMOS camera in Figure 47 is off-axis with respect to the BS communications aperture. This implies that the localization coordinates given by the CMOS camera need to be transformed so that they are referenced to the communications path.

To illustrate the problem, Figure 48 shows a schematic of the BS. The camera aperture is at the origin of the BS plane with no loss of generality. The communications aperture is offset by (H_l^0, V_l^0) in the same plane. The figure also shows the communications beam (green solid line)

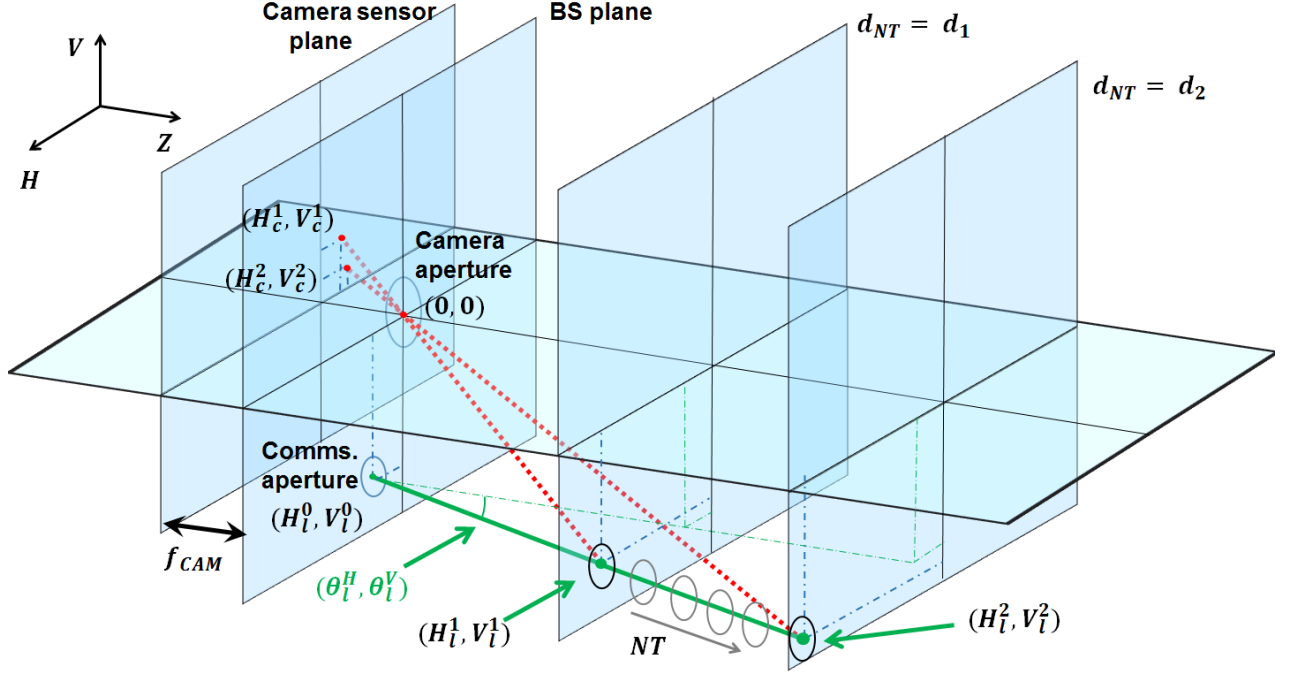


Figure 48. BS 3D schematic. The sketch shows the imaging of two points in the camera plane (lines in red). The communications beam is also depicted using a solid green line.

where $\theta_l = (\theta_l^H, \theta_l^V)$ are the link's horizontal (H) and vertical (V) angular components. The intersection (H_l^1, V_l^1) and (H_l^2, V_l^2) of this beam with two planes at distances d_1 and d_2 , respectively are also given. The images of these two points in the camera sensor plane are (H_c^1, V_c^1) and (H_c^2, V_c^2) , respectively, as outlined by the red dotted lines.

Let us assume that the beam is pointing at the NT, e.g. the NT aperture is located at (H_l^1, V_l^1) in the plane $d_{NT} = d_1$. If the NT moves to (H_l^2, V_l^2) , then the link is still aligned but the image camera registers a shift X_{sh} given by:

$$X_{sh} = \frac{X_l^0 + d_2 \tan \theta_l^X}{1 - d_2/f_{CAM}} - \frac{X_l^0 + d_1 \tan \theta_l^X}{1 - d_1/f_{CAM}} \quad (24)$$

Where $X = \{H, V\}$ and f_{CAM} is the camera lens' focal length. Considering $d_{NT} \gg f_{CAM}$, then equation (24) simplifies to:

$$X_{sh}(d_1, d_2) = f_{CAM} \cdot X_l^0 \left(\frac{1}{d_1} - \frac{1}{d_2} \right) \quad (25)$$

Equation (25) is convenient as there is no dependence on θ_l .

The system calibration consists of finding a relationship between the camera image coordinates (H_c, V_c) and the link angle $\theta_l = (\theta_l^H, \theta_l^V)$, needed to accurately point at the NT aperture with coordinates (H_l, V_l) in an arbitrary plane $d_{NT} = d$. For this purpose, a calibration plane at a distance d_{CAL} from the BS is chosen. In the camera sensor plane, the coordinates (H_c^0, V_c^0) are calculated for a test NT aperture aligned with the communications beam when no steering is applied, i.e. $\theta_l = 0$. Then, using geometric arguments it can be shown that,

$$\theta_l^X(X_c, d) = \tan^{-1} \left[\frac{1}{f_{CAM}} (X_c - X_c^0 - X_{sh}(d_{CAL}, d)) \right] \quad (26)$$

Equation (26) is a closed form function between the camera coordinates X_c ($X = \{H, V\}$) and the link angle θ_l using the correction $X_{sh}(d_{CAL}, d)$ as the NT range d changes. However, a steering system with linear angular magnification and circular symmetry for the SLM-AM module is required to use the previous calibration. From section 3.4.1, the SLM-AM presented quasi-linear beamsteering and asymmetric correction for AM aberrations. Therefore, further calibration is needed to find an empirical form for (26) where a calibration plane (at distance d_{CAL} from the BS) is mapped onto the camera sensor plane. The procedure is as follows, referring to Figure 48:

1. A calibration plane $d_{NT} = d_{CAL}$ is chosen with NT aperture coordinates (H_l^1, V_l^1) .
2. A 2D scan is performed by varying (H_l^1, V_l^1) for N_{scan} points. For each scanning point, the steering action $(\theta_l^H, \theta_l^V) = h(H_l^1, V_l^1)$ and camera plane coordinates $(H_c^1, V_c^1) = g(H_l^1, V_l^1)$ are recorded. A discrete map is then established between (θ_l^H, θ_l^V) and (H_c^1, V_c^1) .

Functions h and g are not known in an exact form and they typically vary from setup to setup.

3. A linear interpolation is generated giving a functional fit $(\theta_l^H, \theta_l^V) = S(H_c^1, V_c^1)$. The higher N_{scan} the more accurate the fit will be.
4. For a general case of an NT at a distance $d_{NT} = d$, instead of equation (26), the following can be used:

$$(\theta_l^H, \theta_l^V) = S(H_c - H_{sh}(d_{CAL}, d), V_c - V_{sh}(d_{CAL}, d)) \quad (27)$$

Equation (27) is used in later experimental sections to calibrate the BS localization system.

4.4 NT TRACKING MODULE

Once the BS points the communications beam at the NT aperture, then the NT has to steer the incoming light so it is aligned with the optical axis of the receiving fibre. Figure 44 shows a PSD based sensing system to accomplish this. A beamsplitter (BSp) is located just after the steering unit, diverting a fraction of the light to the PSD. Subsequently, a lens focuses this light in the PSD plane. In operation, an iterative procedure is used, in which the SLM moves the sampled beam to the centre of the PSD. This point corresponds to the steering with optimal power coupling into the receiving fibre, provided the appropriate mechanical pre-alignment.

A proof-of-principle system based on a quadrant photodetector (Quad) was developed. The design choice was based on commercial availability and cost. Other PSD devices such as lateral effect sensors or InGaAs cameras can also be used. In the following sections the Quad-lens design is first studied. Then, the iterative algorithm to centre the beam footprint in the Quad active area is addressed.

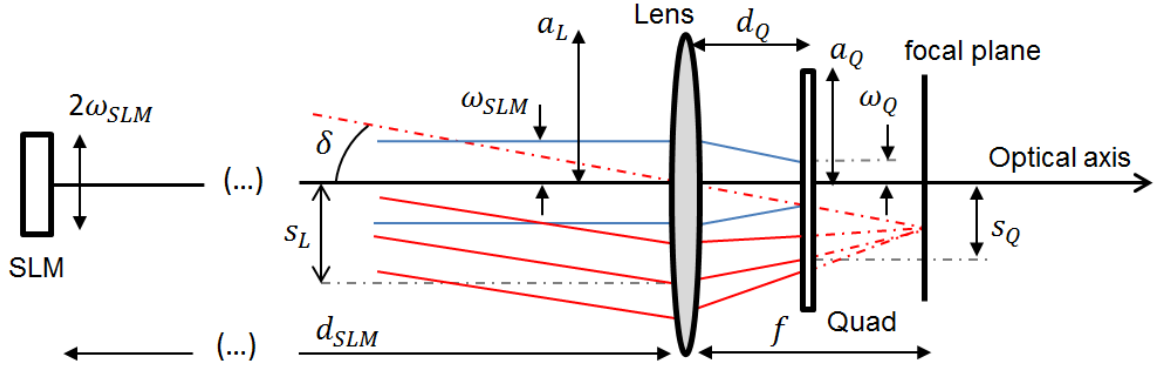


Figure 49. Quad design layout. Ray tracing from the SLM to the Quad for the un-deflected on-axis beam (blue lines) and the steered off-axis beam (red lines).

4.4.1 Quad-lens design

A schematic of the NT tracker is given in Figure 49. The communications beam reflects off an SLM with an active area ω_{SLM} and a steering range $\pm\delta$. Then, it propagates for a distance d_{SLM} before illuminating a lens with aperture radius a_L and focal lens f_Q . This lens focuses the beam onto a Quad detector located at a distance $d_Q < f_Q$. The radius of the Quad active area is a_Q . Ray tracing theory using an ideal thin lens gives:

$$\omega_Q = \left(1 - \frac{d_Q}{f_Q}\right) \omega_{SLM} ; S_L = d_{SLM} \delta ; \quad (28)$$

$$S_Q = \left[\frac{\omega_Q d_{SLM}}{\omega_{SLM}} + f_Q \left(1 - \frac{\omega_Q}{\omega_{SLM}}\right) \right] \delta$$

Where ω_Q is the beam radius in the Quad plane. S_L and S_Q are the beam walk-off in the lens and Quad planes, respectively. The NT tracker needs to satisfy the following conditions:

1. $S_L < a_L$ to avoid beam vignetting at the lens. d_{SLM} can be chosen based on the SLM steering range $\pm\delta$.

2. $\omega_Q < a_Q$ so that the Quad active area is not overfilled. This condition can be easily achieved by adjusting the lens to Quad distance d_Q in equation (28).
3. Beam walk-off $\Delta S_Q > \tau$ in the Quad plane for a beamsteering difference $\Delta\delta$. Here τ is the Quad sensitivity to beam displacements and $\Delta\delta$ is required steering accuracy.

Equation (28) shows that a lens with a large focal lens f_Q makes it easier to meet the 3rd condition by enhancing the beam walk-off on the Quad to achieve $\Delta S_Q > \tau$.

4.4.2 Quad search and tracking algorithms

The previous section described a feasible Quad lens design. However, if a lens with a large focal length f_Q is chosen, the beam walk-off range in the Quad plane, assuming $d_Q \sim f_Q$ would be $\Delta S_Q(\pm\delta) = \pm\delta \cdot f_Q$. This corresponds to a full displacement of $S_Q = 2\delta \cdot f_Q \gg a_Q$ in the Quad plane, which is $N_{vec} = \delta \cdot f_Q / a_Q$ times larger than the Quad active area diameter $2a_Q$. Therefore, a search algorithm is needed to first bring the beam spot onto the Quad active area, followed by an iterative procedure to centre the spot on the Quad. The corresponding flowchart is shown in Figure 50 for the simplified case of centring the beam in the horizontal axis (parallel to the optical table). A similar procedure is required for the vertical direction (perpendicular to the optical table) to achieve 2D tracking.

In the Quad plane, the horizontal axis is divided into small intervals of size $2a_Q$. The search initial state ($ST = 1$) uses a vector $\boldsymbol{\varphi}_{vec}$ with $|\varphi_{vec}(i+1) - \varphi_{vec}(i)| = \delta$, $i = \{1, 2, \dots, N_{vec}\}$ steering points corresponding to the centre of the small intervals. The NT SLM is continuously scanning through this vector until light is detected by the Quad ($OP_Q > TH_{OP}$, here TH_{OP} is a predefined optical power threshold). The tracking state ($ST = 2$) is then turned on. The beam is iteratively

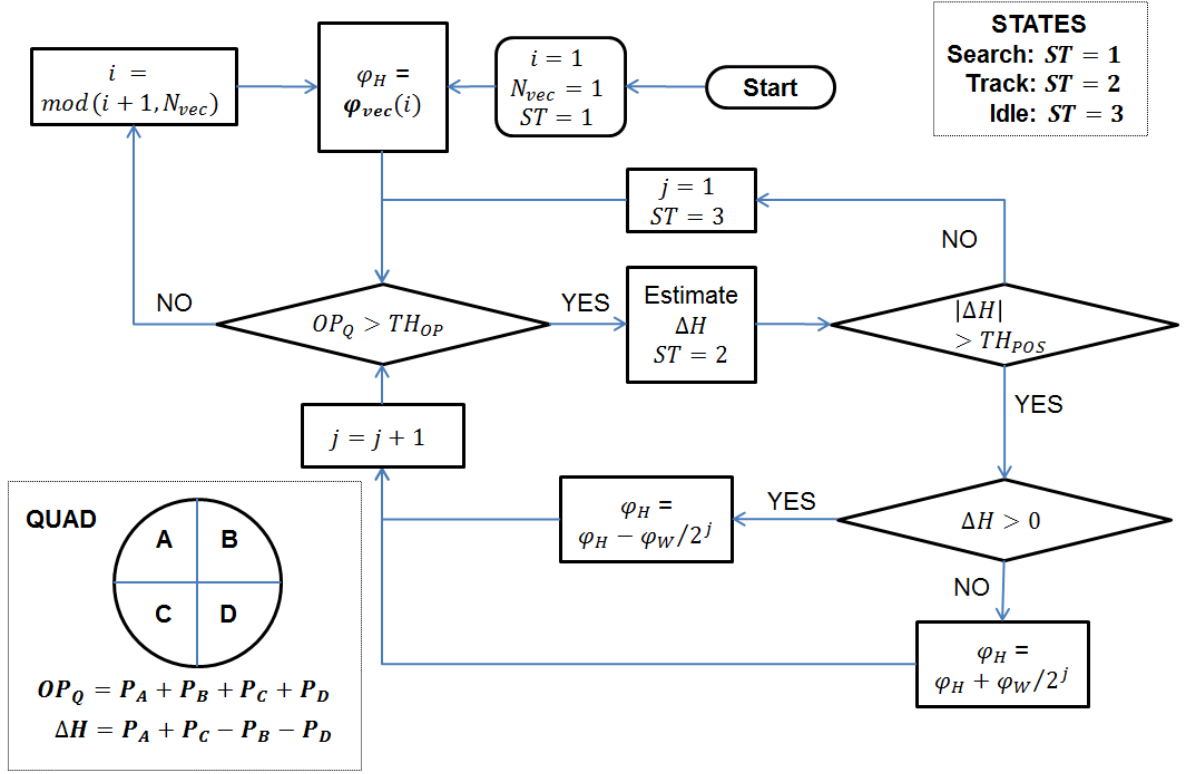


Figure 50. Flowchart for the search and iterative tracking algorithms. TH_{OP} is the optical power decision threshold in the search state. TH_{POS} is the decision threshold in the tracking state. ϕ_W is the constant steering increment in ϕ_{vec} , i.e. $\phi_W = \phi_{vec}(i + 1) - \phi_{vec}(i)$, $i = \{1, 2, \dots, N_{vec}\}$.

steered to the centre depending on the sign of the Quad differential reading $\Delta H = P_A + P_C - P_B - P_D$. Once $|\Delta H|$ is below a predefined threshold TH_{POS} , then the beam is considered aligned. The system passes to an idle state ($ST = 3$) until either the beam moves away from the Quad centre ($|\Delta H| > TH_{POS}$) or altogether out of the Quad active area ($OP_Q > TH_{OP}$).

The iteration in the tracking state ($S = 2$) is required because the Quad gives limited information about the beam position. That is, although these type of devices are high precision position sensors [85], they also require clean transverse profiles to estimate the beam position [86]. In the experiments, the beam is far from a perfect Gaussian or other known deterministic profile due to

geometrical aberrations and aperture vignetting distortions. Therefore, only by the optical power sum OP_Q and differential signal ΔH is used. These signals are used as decision threshold to perform the search and tracking steps as shown in the flow chart in Figure 50. Other PSD devices such as lateral effect sensors or InGaAs 1550 nm camera could, in principle give a direct reading on the beam position with higher degree of independence on the beam profile. These devices are good candidates for future implementations that might require a faster tracking response.

In the experiments, the NT was considered moving mainly in the horizontal axis (in the plane parallel to the optical table). Thus, the search algorithm was kept in 1D. The tracking function was implemented for both the horizontal and vertical directions. For the vertical direction, this is straightforward by using a vertical steering variable φ_V as and the Quad vertical reading $\Delta V = P_A + P_B - P_C - P_D$. If the search algorithm were to be extended to 2D, the vector $\boldsymbol{\varphi}_{vec}$ becomes a matrix with N_Q^2 elements, which would slow down the process.

4.5 PRELIMINARY EXPERIMENTS

Preliminary experiments were carried out to test the BS localization and NT tracking modules independently.

4.5.1 BS localization

The CMOS camera performance was initially tested. The LED ring was located at a distance of 3 m. The image was captured every second for 100 seconds, and the LED ring centre was estimated for all $N = 100$ images. The largest deviation between any two centres in the sample was found to be 0.2 pixels. This corresponds to an angular error of 0.05° or 2.5 mm for $d_{NT} = 3$ m. Therefore the proposed camera based localization system is sufficiently accurate.

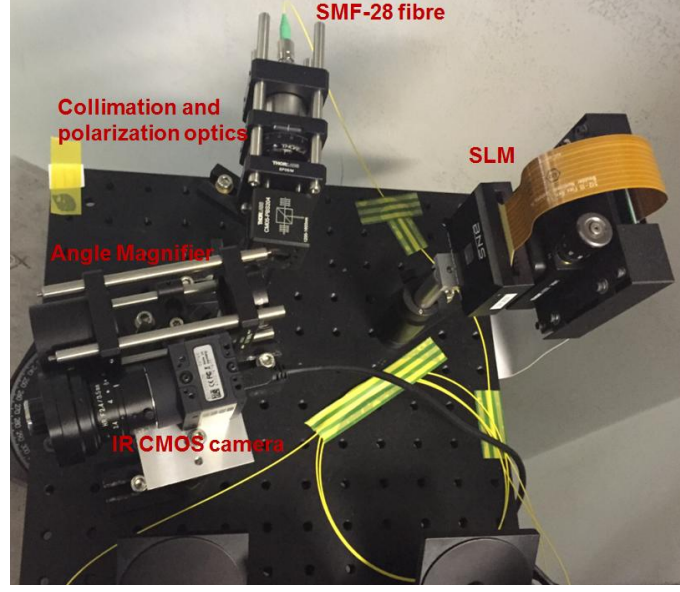


Figure 51. Base station experimental layout including the IR localization CMOS camera.

The required BS calibration described in section 4.3.3 was also carried out using the experimental setup shown in Figure 51. The CMOS camera was placed next to an angle magnifier (AM)-SLM beamsteering module with an overall $\text{FOV} = \pm 30^\circ$. The SLM not only performed the basic steering function but also corrected for geometrical aberrations introduced by the AM. It was deduced that $N_{scan} = 12$ was sufficient for a 1D horizontal steering calibration. This is equivalent to having a calibration point every 5° . A 2D calibration was not needed as the experiments were kept in a plane parallel to the optical table.

4.5.2 NT tracking

The NT tracker requires a steering accuracy of $\Delta\delta = 0.1^\circ$ as shown in Figure 45 (b). For the Quad-lens design a lens (Thorlabs AC254) with $f_Q = 500 \text{ mm}$ and clear aperture $a_L \sim 11.5 \text{ mm}$ was chosen. A Quad (Thorlabs PDQ30C) with $a_Q = 1.5 \text{ mm}$ was used. Considering a beamsteering SLM (BNS HSP512-1550) with an active area $\omega_{SLM} \sim 3.5 \text{ mm}$ and a steering range $\delta = \pm 3^\circ$,

$\Delta S_Q(\delta = \pm 3^\circ) = \pm 26.2$ mm is obtained by fixing $d_Q \sim f_Q$. This corresponds to a full displacement of 52.4 mm in the Quad plane, which is ~ 17 times larger than the Quad active area diameter $2a_Q = 3$ mm. Therefore, a software-based (MATLAB) search and tracking system was implemented based on the flowchart in Figure 50 with $N_{vec} = 17$.

An SLM to lens distance $d_{SLM} \sim 100$ mm was also set to avoid any vignetting of the incident beam beyond the lens aperture. The final NT setup including the Quad is shown in Figure 52. The next section describes the joint performance of the BS and NT in a functional ultra-high data rate link.

4.6 TRANSMISSION EXPERIMENT

A test-bed was designed to characterize the IR localization at the BS as well as the NT Quad-based alignment as function of the link angle θ_l . Figure 53 shows the corresponding schematic. The BS is mounted on a rotation stage driven by a Newport ESP300 driver with 0.0002° accuracy. The rotation axis is located at the AM exit aperture defining the BS link angle θ_l^{BS} with very high

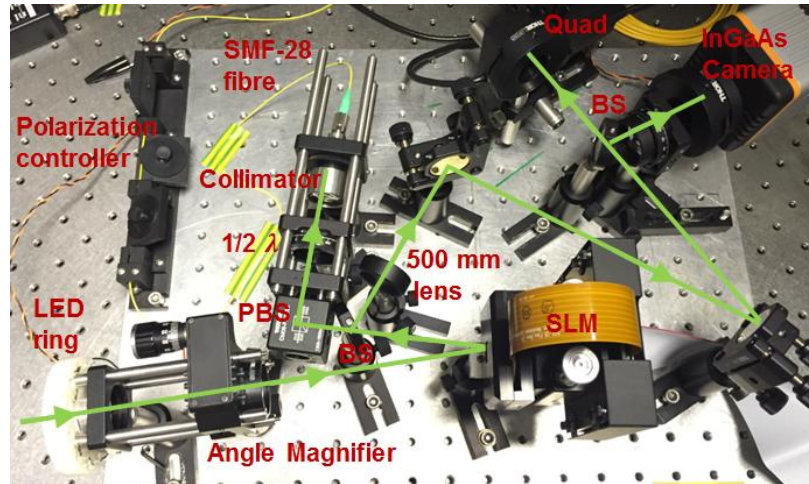


Figure 52. NT experimental layout with the added Quad tracking components.

precision. The NT receiver is located at a distance of $Z = 2.8$ m. The NT is mounted on a breadboard that can be manually rotated around its AM entrance aperture. This determines the NT link angle θ_l^{NT} .

The IR localization at the BS and the NT Quad-based alignment were implemented in Matlab[®] using different PCs for each transceiver. The alignment performance was characterized using either a CW 1550 nm laser or a coherent transmission system. In the following sections these experiments are discussed in detail.

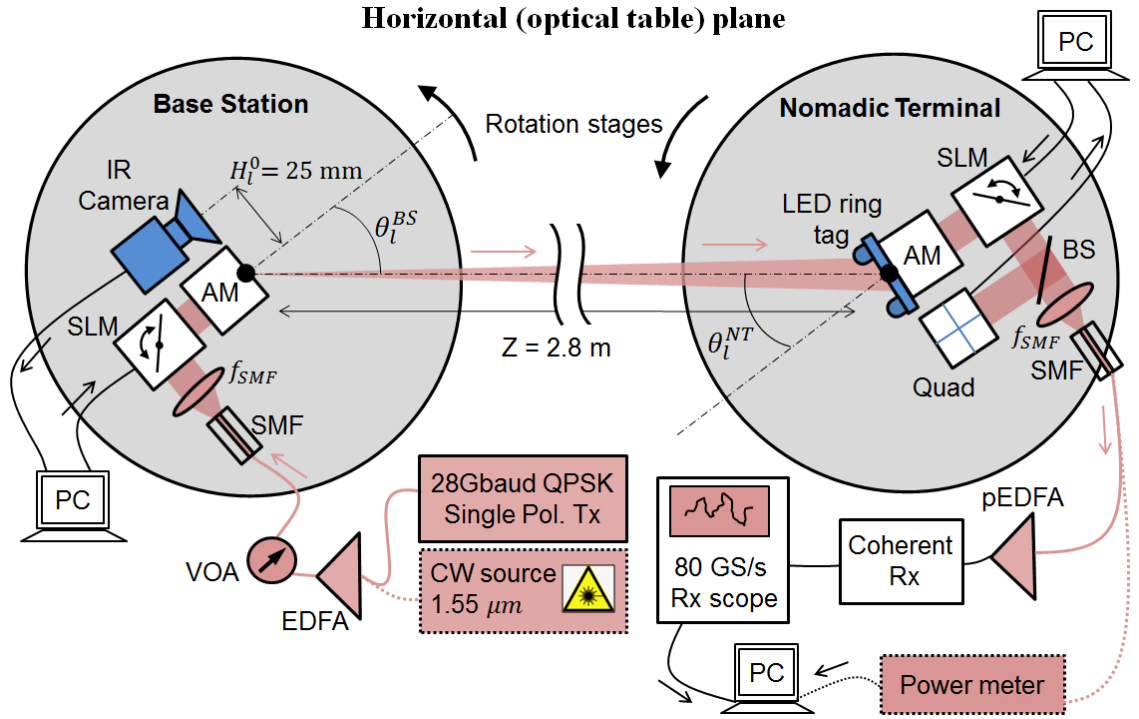


Figure 53. Communications test-bed. The base station and the nomadic terminal are mounted on rotation stages. BS is a beamsplitter with 90% transmission / 10 % reflection coefficients. Also, $f_{SLM} = 37$ mm is the focal length of a SMF pigtailed focusing lens with $NA = 0.24$. VOA is a variable optical attenuator; pEDFA is a preamplifier EDFA.

4.6.1 CW study

A 1550 nm CW laser was connected to the BS. The BS station was rotated to an arbitrary angle θ_l^{BS} . The NT was also rotated to an approximate equal angle $\theta_l^{NT} \sim \theta_l^{BS}$. Provided a proper calibration of the IR localization and NT Quad-based tracking systems, an automated link alignment can be successfully established after several seconds. This is why the system is considered nomadic rather than mobile (the use of faster components in future implementations could make the system respond in real-time).

The link operation consists of two phases:

1. Transient phase: The BS localization and / or NT tracking has not been completed. In this transient phase the BS localizes the NT and sends the communications downlink. Then, the NT tracking is performed. Once both the BS localization and NT tracking are accomplished, the system moves to a stable phase.
2. Stable phase: the link remains aligned subject to minor perturbations due to mechanical vibrations, small NT movements within the communications beam footprint, or other sources of errors. If the search state is activated for the NT tracking (see Figure 50), then the system returns to the transient phase.

For a stable link, Figure 54 shows a comparison between the manually optimized alignment and the automated BS localization. The error bars are generated from 1 million coupled power measurements captured over a 100 second window. A sampling rate of 10kHz allowed us to record fast power reading perturbations whilst in the stable phase. It can be seen that the automated BS localization adds a penalty of maximum 3 dB for the scanned FOV of 30°. No significant additional drop is seen in the received optical power when including the NT Quad-based tracking.

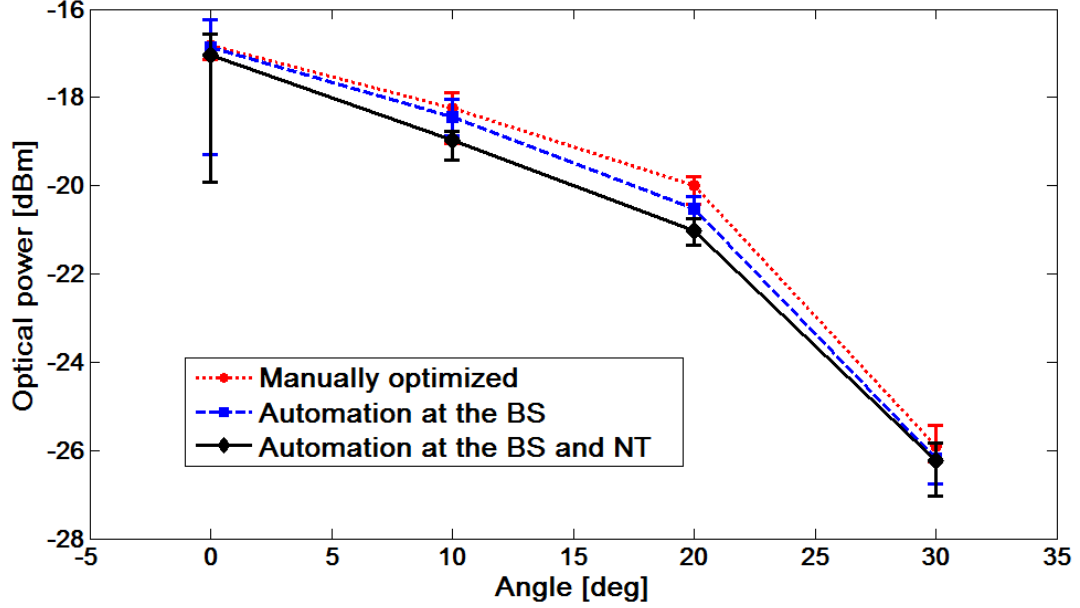


Figure 54. Coupled optical power at the NT as a function of the link angle θ_l . The alignment was either manually optimized, automated for the BS localization system or automated for both the BS localization and NT tracking systems.

NT displacements beyond ~ 10 mm can take the system back to the transient phase. The corresponding recovery response is variable and depends on the NT motion speed and new position. The blockage of the BS-NT line-of-sight (LOS) also brings the system into the transient phase but the process is more predictable. If the LOS between the BS and NT is lost, then the BS memorizes its previous position until the beacon reappears. However, the NT goes to a beam search state (see Figure 50) scanning through the whole FOV to steer the beam back to the Quad active area. The recovery time of the system after momentarily blocking the communications beam is shown in Figure 55. It can be seen that it takes ~ 5 seconds for the coupled optical power to stabilize.

Finally, the BS localization and tracking response in the stable phase was studied. For this purpose, the BS was rotated in steps of 0.1° around $\theta_l = 30^\circ$. This corresponds to a NT

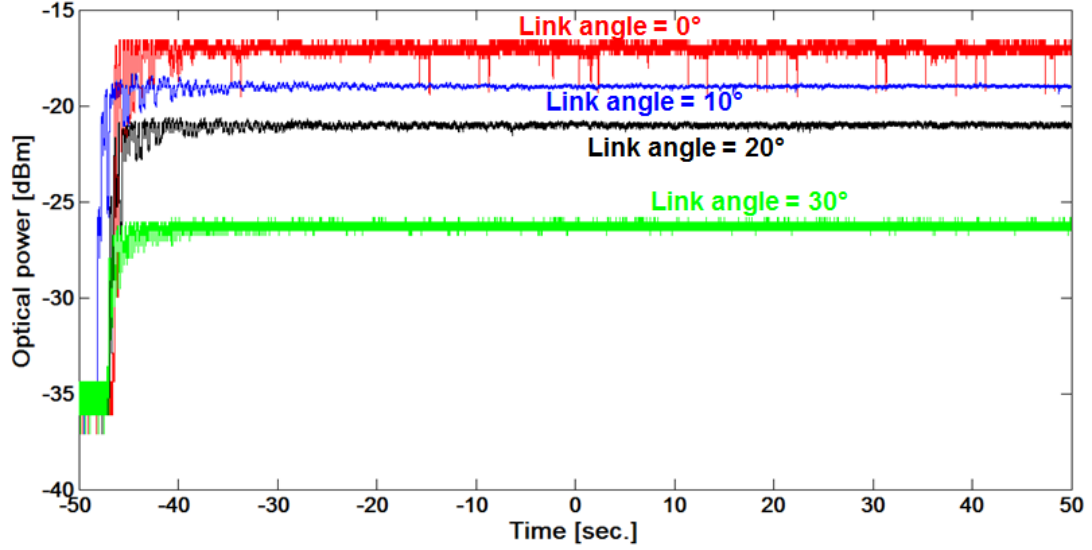


Figure 55. Recovery time after a beam link blockage. The coupled optical power at the NT is shown as a function of the link angle θ_l .

displacement of ~ 5 mm at a BS-NT distance of $Z = 2.8$ m. In this case, the beam is misaligned but still illuminates the NT aperture. The results are given in Figure 56. The BS localization and NT tracking recover the link in less than 5 seconds. With no automated alignment, there is a permanent drop (as much as 3 dB) in the received power.

4.6.2 Communications link

So far the BS-NT automated alignment for a CW beam has been studied. In this section the performance of a coherent transmission link subject to the effects of the automated alignment is investigated. For this purpose, a 28Gbaud QPSK single polarization transmitter [87] is connected to the BS via an EDFA as shown in Figure 53. Also, the NT SMF is connected to an intradyne coherent receiver via a removable preamplifier EDFA. The receiver output signal is finally captured by a real-time oscilloscope sampling at 80 GS/s. The transmission tests last for ~ 38 μ s which corresponds to the length of the oscilloscope sampling window. Further off-line processing

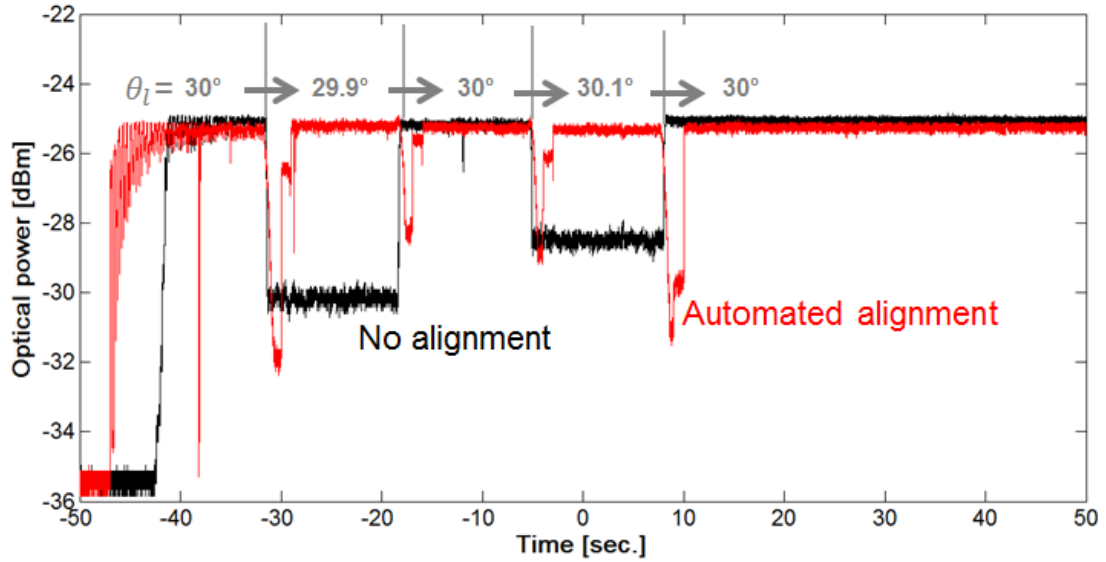


Figure 56. Received optical power at the NT as a function of time. The red curve corresponds to an automated tracking for the BS and NT. The black curve is for a system with no tracking.

takes ~ 1 min. Therefore, the transient phase of the automated alignment process can not be monitored using the transmission system. The link's stable phase once the BS and NT are aligned is instead analysed.

Figure 57 shows the sensitivity curves for different link angles θ_l and the optional use of the BS tracking and / or EDFA pre-amplifier. The EDFA pre-amplifier is included as it can potentially increase the link budget. It can be seen that the sensitivity is independent of the NT tracking and link angles with a ~ 1 dB penalty at the forward error correction (FEC) limit, with and without optical pre-amplification. However, the removal of the EDFA preamplifier produces an average of ~ 7 dB drop in the link margin.

To characterize the BS localization system, a statistical approach was used, in which a 100 set of communications transmission data were gathered with a 1 minute difference between consecutive runs, which is sufficient to allow data to be processed between runs. The variable optical

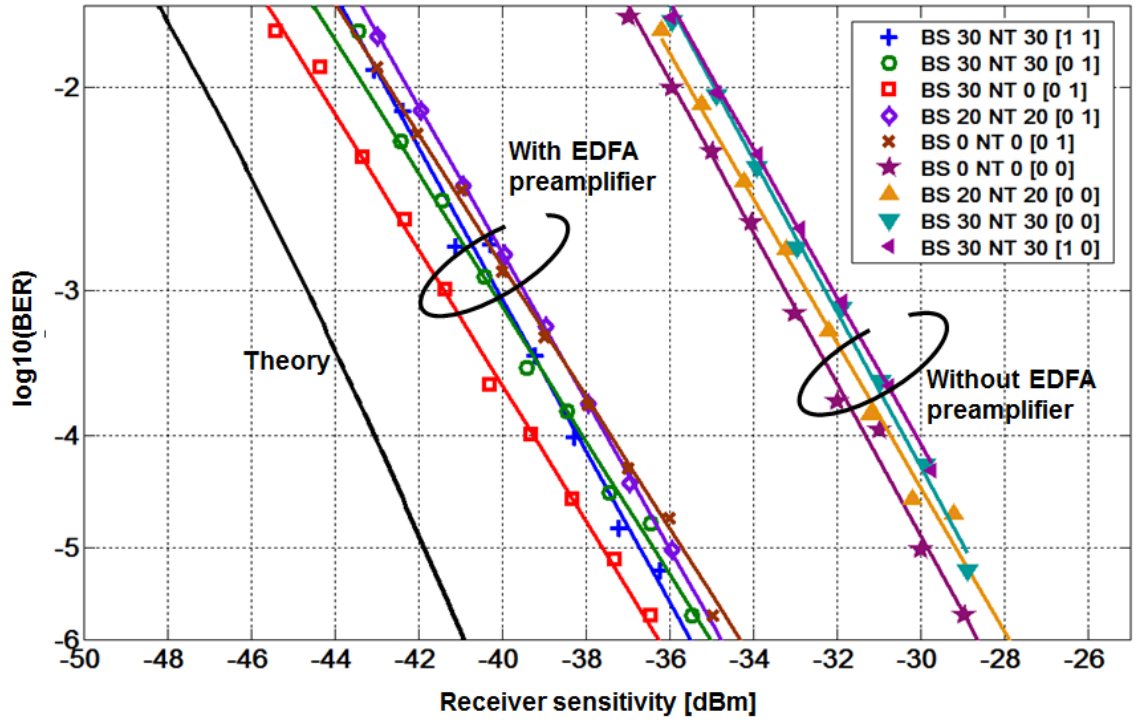


Figure 57. Coherent receiver sensitivity. The inset legend reads “BS θ_l^{BS} NT θ_l^{NT} [TR PA]” where θ_l^{BS} and θ_l^{NT} are the BS and NT beamsteering angle, respectively. In the [TR PA] vector, TR = 1 means the NT localization is ON and PA = 1 means there is optical pre-amplification. The theoretical curves were taken from [72].

attenuator (VOA) was set such that system performance was near the FEC limit of the coherent receiver. Results are given in Figure 58. The histograms show a less than 1 dB broadening in the sample distribution due to the BS localization error described in section 4.5.1.

Finally, the link BER performance as a function of the VOA attenuation was measured, whilst keeping the BS optical output power at 10 dBm (the 1550 nm eye-safe limit). Figure 59 shows the results for different configurations depending on the use of BS localization, EDFA pre-amplification and link angle. For each configuration, the interception of the plotted curve with the FEC limit gives the available power budget, i.e. the maximum allowed optical loss in an error-free communications link. The following conclusions can be drawn:

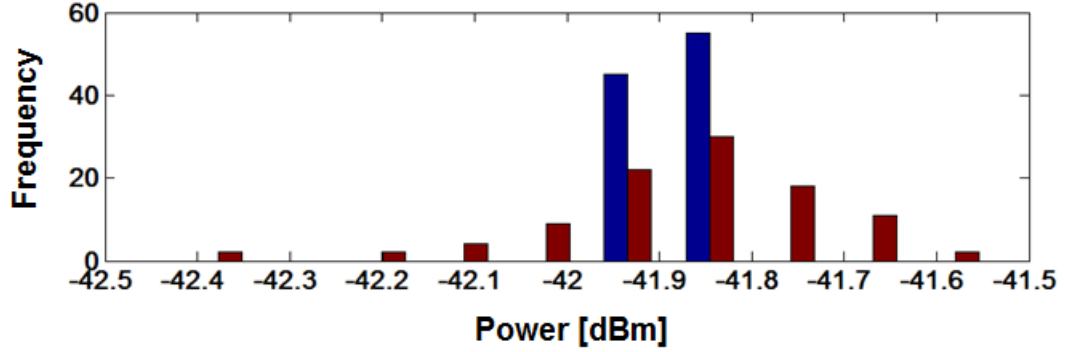


Figure 58. Histograms of optical power for the coherent receiver.

1. The power budget is independent of the BS link angle θ_l^{BS} . This is clear from the rightmost curves where the θ_l^{BS} changes from 0° to 30° with negligible impact. A simple explanation is that any loss inside the BS (as θ_l^{BS} increases) is compensated by an increase in the booster EDFA gain to keep the BS output beam at the 10 dBm eye-safe limit.
2. The power budget is nonlinearly affected by the NT angle θ_l^{NT} . From $\theta_l^{NT} = 0^\circ$ to 20° the drop is ~ 4 dB for both configurations (with and without EDFA preamplifier). However, from $\theta_l^{NT} = 20^\circ$ to 30° the link loss increases by as much as 7 dB. This is because, for large link angles, the NT introduces much higher geometrical aberrations, vignetting and steering losses which reduces the optical coupling into the receiver SMF fibre.
3. The automated BS localization at $\theta_l = 30^\circ$ produces a power budget reduction of up to ~ 2 dB. This is due to errors in the localization pre-calibration. An optimization of the calibration process should eliminate this drop.
4. The use of an EDFA preamplifier improves the link budget by at least 6 dB. This is in agreement with the sensitivity results given in Figure 57.

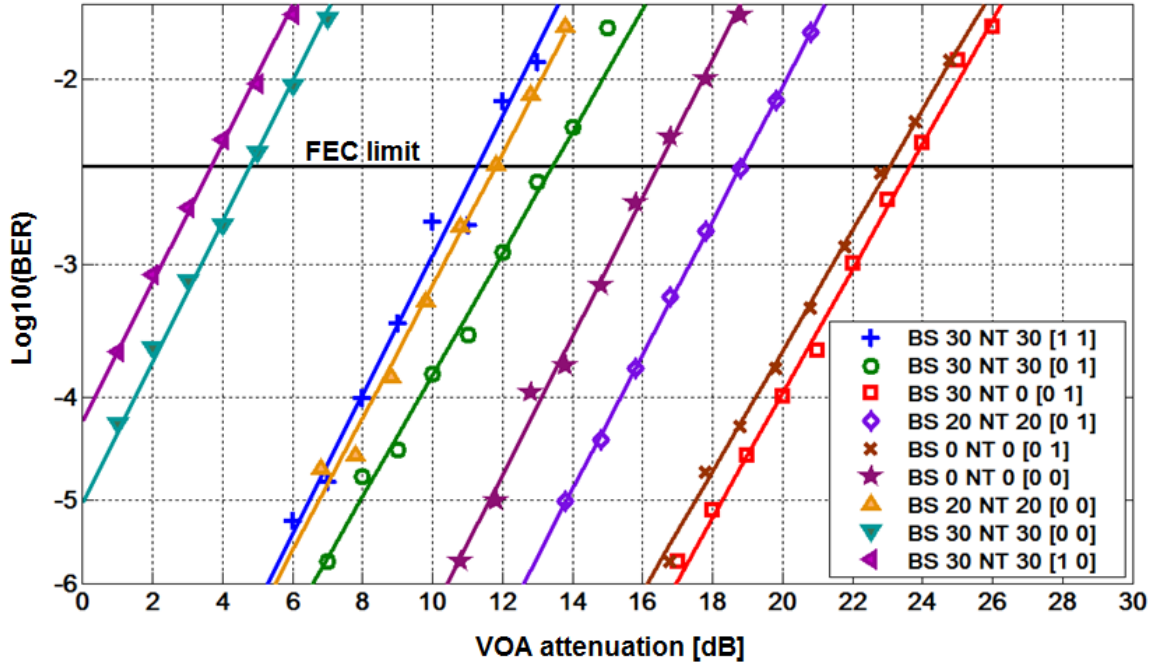


Figure 59. BER vs VOA attenuation. The inset legend reads “BS θ_l^{BS} NT θ_l^{NT} [TR PA]” where θ_l^{BS} and θ_l^{NT} are the BS and NT beamsteering angle, respectively. In the [TR PA] vector, TR = 1 means the BS tracking is ON and PA = 1 means there is optical pre-amplification.

4.7 CONCLUSIONS

In this chapter, a localization and tracking system has been successfully designed and implemented, suitable for ultrafast narrow beam indoor OWC requiring alignment at both ends of the link. A BS localization accuracy of 0.05° was achieved for an SMF-wireless-SMF geometry. Using this system, a 50 Gb/s QPSK coherent transmission with automated alignment for the whole FOV of $\pm 30^\circ$ at a range of up to 2.8 m was demonstrated. The localization and tracking systems added penalties of up to 3 dB compared to the manually aligned cases. Also, the use of an EDFA preamplifier at the receiver improved the link margin by as much as 7 dB.

Data rates above the 100 Gb/s are possible as shown in Chapter 3 The 50 Gb/s QPSK coherent transmission system was chosen due to its availability at the time of the experiments. This nomadic demonstration shows the potential of narrow beam indoor mobile wireless communications in future indoor applications.

Chapter 5

Point-to-multipoint communications

5.1 OVERVIEW

In previous chapters, an indoor point-to-point (PtoP) system where a static BS communicates with a single NT was studied. For this link, data rates of up to 400 Gb/s were demonstrated in Chapter 3 using WDM techniques. In general though, the traffic demand will be distributed over several NTs. Each NT will require a different data rate, variable in time and space. Therefore, a point-to-multipoint (PtoM) architecture will be needed to address this dynamic traffic demand.

Liang et al. [88] have proposed a demultiplexing (demux)-PtoM scheme using a passive dispersive element (PDE) at the BS. In their approach, each subcarrier of the WDM comb is routed to a particular area of the room. This is a suitable solution as long as the traffic demand is uniform throughout the coverage area. In this chapter, the abovementioned demux-PtoM system is enhanced by using an SLM. The SLM advantage is that reconfigurable diffraction patterns can be programmed. Therefore, the proposed system can potentially address a dynamic traffic demand.

Two PtoM principles are proposed based on the SLM capabilities:

1. Division of aperture (DOA): the SLM is spatially divided into independently programmable sectors. Each sector steers the corresponding incident light to a unique direction.
2. Division of wavefront (DOW): the SLM generates a diffraction pattern that is transformed into multiple beams in the far field. The aperture is not spatially divided. The beamsteering is accomplished by constructive and destructive interference of the original incident beam after reflection from the SLM.

In this chapter, experiments are carried out to study both PtoM principles.

5.2 DEMULTIPLEXING ARCHITECTURES

Combining PDEs and SLMs can provide flexible and reconfigurable BS access points based on WDM systems. Figure 60 shows two possible architectures with PtoM capabilities. The number of WDM channels is arbitrarily set to 4 for visualization purposes. The first architecture (see Figure 60 (a)) combines a PDE with an SLM beamsteering unit. The PDE spatially separates the different subcarriers, thus demultiplexing the incoming beam. The separated beams are then incident on different sectors of the SLM active area allowing a DOA. This way the BS architecture can independently steer each beam to a different NT. The second architecture (Figure 60 (b)) removes the PDE from the BS, thus the demux function is not performed. Instead, the SLM generates multiple beams using either DOA or DOW, with each beam carrying the entire WDM capacity. If

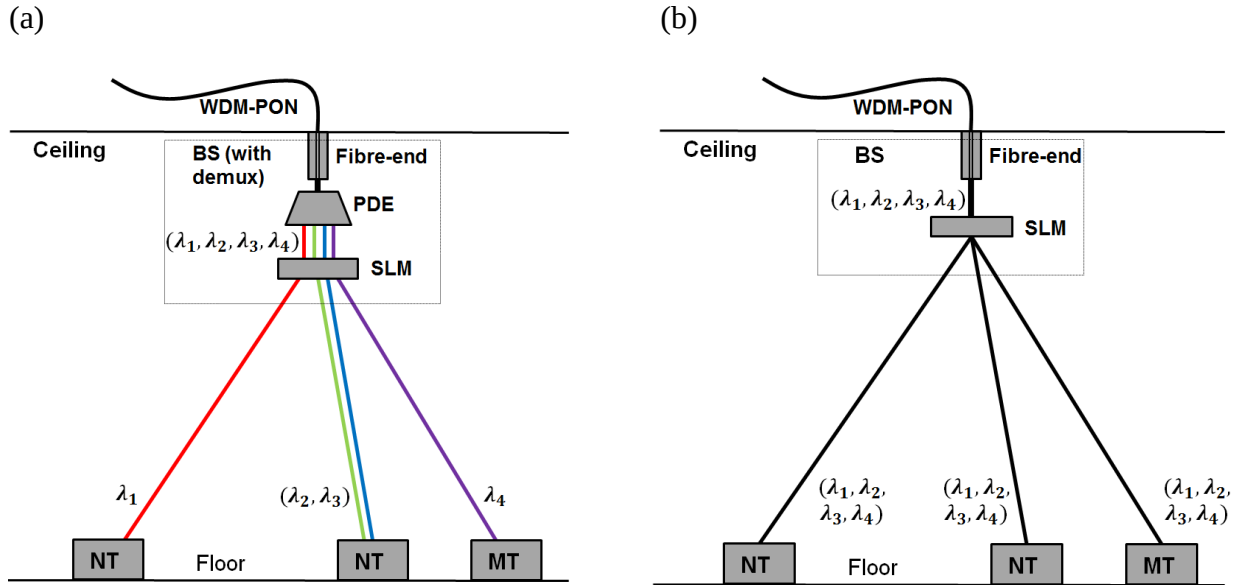


Figure 60. WDM distribution system schematic with demultiplexing at (a) the BS and (b) the NTs. The wavelengths $\lambda_1 \dots \lambda_4$ are part of a to a WDM comb. PDE is a passive dispersive element.

required, the demux function is subsequently carried out at the NT end.

5.3 POINT-TO-MULTIPOINT TESTS

In this section, three tests are defined to characterize the PtoM architectures given in Figure 60. DOA and DOW principles are used. For each test, a simplified 2-beam generation problem is studied. These are summarised in Figure 61 where the SLM aperture illumination and hologram profiles are outlined for each individual case. Either 2-beam or a single beam illumination is considered. The 2-beam illumination corresponds to applying the wavelength demux PDE before the SLM.

The three PtoM tests are listed below:

1. Demux-DOA: The test is derived from Figure 60 (a). Two beams are generated after the PDE. These are then incident on the SLM as shown in Figure 61 (a). The SLM is partitioned into two programmable sectors. Programmable diffractions gratings (see section

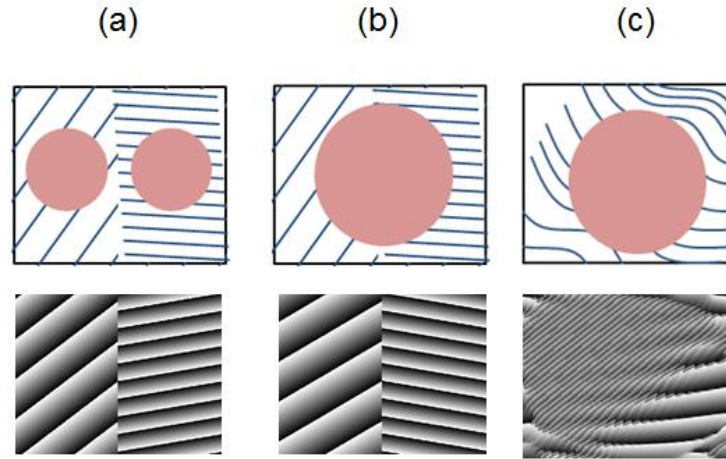


Figure 61. Illumination profiles sketches (upper row) and SLM hologram (lower row) for (a) two small beams and DOA (b) a single large beam with DOA, and (c) a single large beam with DOW.

2.5.3) are then applied to each sector.

2. DOA: The test is derived from Figure 60 (b). A single beam illuminates the SLM active area as given in Figure 61 (b). The SLM is divided into two independently programmable sectors to achieve the 2-beam PtoM capability. Dynamic diffraction gratings are then applied to each sector.
3. DOW: The test is derived from Figure 60 (b). A single beam illuminates the SLM active area as shown in Figure 61 (c). A complex hologram is programmed to diffract the incident light such that 2 beams in the far field are generated by means of constructive and destructive interference.

The DOW hologram is generated by means of an iterative algorithm referred to as Gerchberg-Saxton (GS). The GS algorithm has been used in other research fields [89]–[91] but, to the best of our knowledge, this is the first time it is used in the context of OWC. The next section studies the GS algorithm for a 2-beam generation problem.

5.3.1 Gerchberg-Saxton algorithm

The GS approach requires an iterative procedure to be able to accommodate the phase-only hologram to the fixed apodization in the SLM plane. The hologram generation algorithm is explained in Figure 62. The process initiates by setting the target field amplitude represented by a discrete matrix H_0 . The non-zero elements in the matrix are the steered beams' positions in a target plane whose scale is determined by the optics after the SLM. The initial phase φ_0 is also randomized. The initial field $U_0(u, v) = H_0 \exp[\varphi_0]$ is then fed into an iteration loop. The first step of the iteration performs a 2D inverse discrete Fourier transform (2D-iDFT) that propagates the field from the reciprocal (target) plane to the SLM plane. This is a discrete version of the

$$H_w(u, v) = f_w(u, v) \cdot H_0(u, v)$$

$$f_w(u, v) = (1 - a) + a \cdot H_0(u, v)/H(u, v) \quad (29)$$

Where $a \in (0,1)$ and it is typically set to 0.5. Equation (29) increases the target value at coordinates containing lower than expected intensity values. The field $H_w(u, v)$ with the same estimated phase $\varphi(u, v)$ is subsequently fed back to the 2D-iDFT to start a new iteration.

The GS algorithm requires N_{iter} iterations to converge to a solution satisfying the target field in the reciprocal plane. In the beamsteering application, it is sufficient that the light is efficiently distributed amongst the different coordinate points in the target plane. This can be achieved using the following metric:

- 1- efficiency (ϵ): the power is diffracted to the target positions.

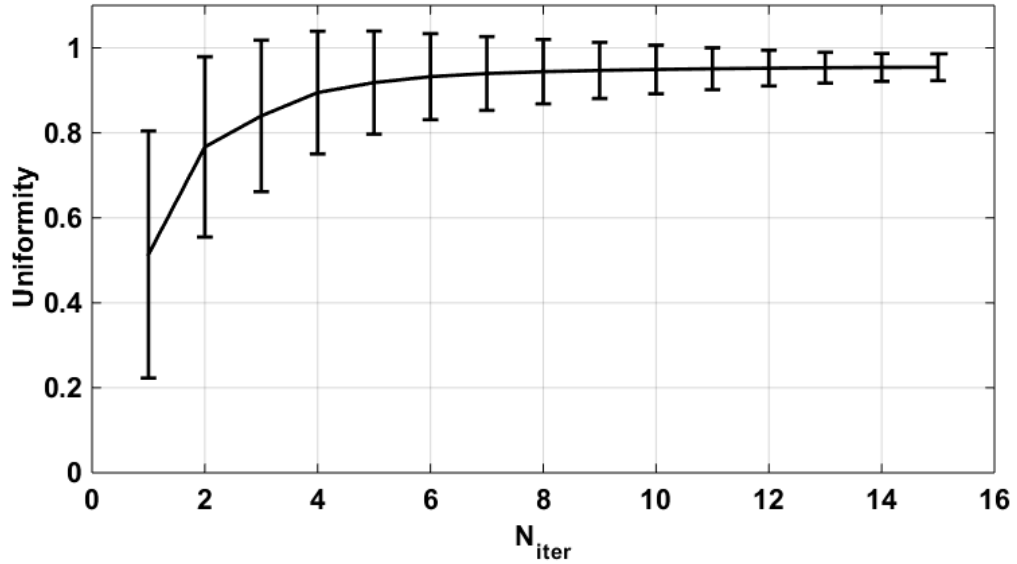


Figure 63. GS convergence for a 2-beam beamsteering problem using the uniformity τ criteria. The error bars give the standard deviation for a dataset of 1 million randomly chosen initial target fields $U_0(u, v)$.

- 2- uniformity (τ): the power is evenly distributed to these positions given by $\tau = 1 - (I_{max} - I_{min}) / (I_{max} + I_{min})$.

For the case of 2-beam beamsteering, Figure 63 shows the uniformity τ as a function of N_{iter} . 1000 pairs of steering coordinates (H_0) and 1000 initial random phases φ_0 were generated for each pair. In total, the GS algorithm was run for $1000 \times 1000 = 1$ million possible fields $U_0 = H_0 \exp[\varphi_0]$ with $N_{iter} = 1 \dots 15$. From Figure 63, it can be seen that $N_{iter} = 10$ gives $\tau > 0.9$, which is an acceptable uniformity. However, there are some initial random phases ($\sim 2\%$) that do not converge to a uniform solution with $\tau < 0.5$. These cases are not plotted in Figure 63 and should be avoided in a practical system, e.g. by using libraries of pre-installed holograms. It was also found that the GS algorithm is highly efficient ($\varepsilon > 0.98$) from $N_{iter} = 1$ and the efficiency does not change as N_{iter} increases.

5.4 EXPERIMENTAL STUDY AND DISCUSSION

Two-beam PtoM generation experiments were carried out to characterize the Demux-DOA, DOA and DOW tests. For the three tests, the free space beam propagation was studied. The corresponding power coupling into a fibre-based NT receiver was also measured using a fibre-based NT receiver.

5.4.1 Experimental setup

The experimental setup is shown in Figure 64. Two fibre laser sources, separated by $\Delta\lambda = 45$ nm are first combined in a 50:50 coupler. The coupler outputs are incident on the SLM 1 using two different paths: the demux or ref. The demux path uses an $f = 8$ mm fibre collimator to generate a 3.5 mm small diameter beam. This beam is then diffracted by a blazed grating (Thorlabs GR13-

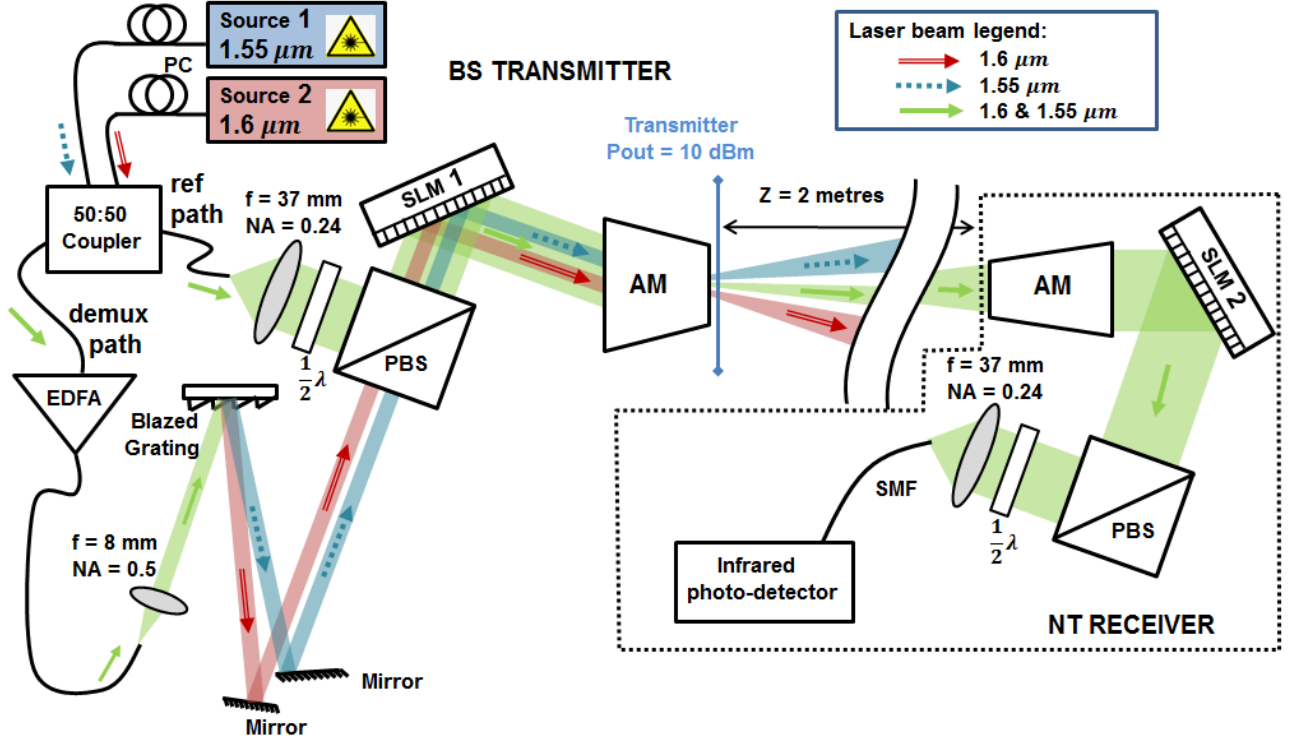


Figure 64. Experimental test-bed. PBS is a polarization beamsplitter and AM is an angle magnifier.

0616) with a blazed wavelength of 1600 nm. The split beam illuminates the SLM as shown in Figure 61 (a). In the ref path, the configuration collimates the combined 1550 nm and 1600 nm sources using an $f = 37$ mm lens to create a 7 mm diameter beam. After some polarization optics, the beam is incident on the SLM 1 as shown in Figure 61 (b) or (c). Finally, for either path configuration the reflected light off the SLM is steered to a passive AM using holograms such as those depicted in Figure 61 (lower row). The BS coverage after the AM has a FOV of $\pm 30^\circ$ as previously characterized in Chapter 3 for a PtoP scenario. The output power is kept at $P_{out} = 10$ dBm for all PtoM configurations.

After $Z \sim 2$ m free space propagation, a receiver NT is fixed to measure the relative link loss between the different PtoM tests. A simplified NT is used as shown in Figure 64 (right). The NT is

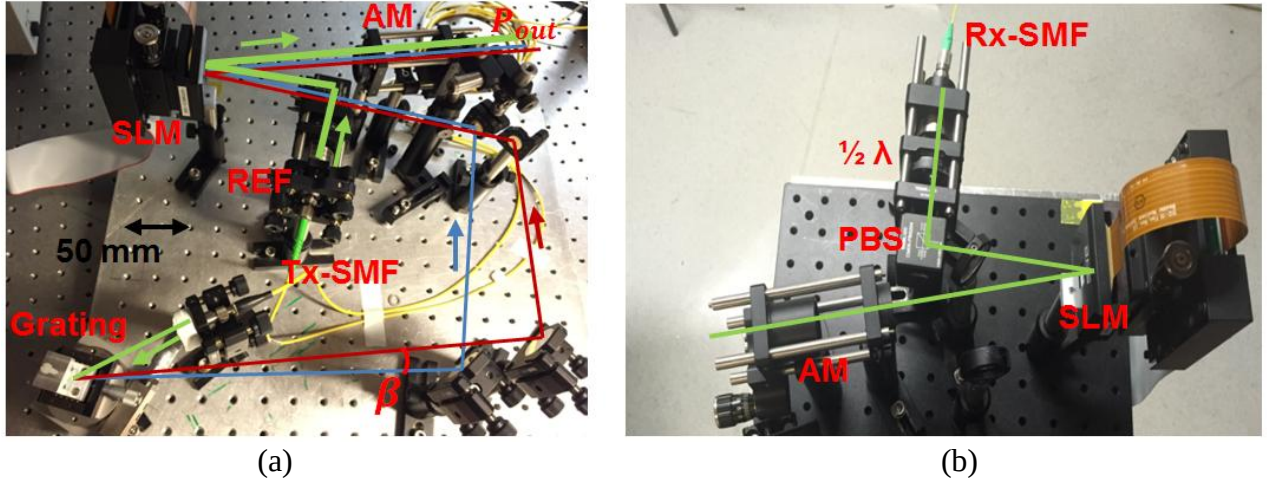


Figure 65. Pictures of the BS transmitter (a) and NT receiver (b). The red line is the 1550 nm beam, the blue line is the 1600 nm beam and the green line is a mix of both.

oriented in the direction of the incoming beam and the corresponding AM magnification was fixed to $\gamma = 5$ (thus having a reduced FOV= $\pm 15^\circ$). This configuration increased the coupled power into the SMF fibre-pigtailed photo-detector relative to those links studied in Chapter 3 and Chapter 4. Finally, due to limited resources a second NT could not be replicated. Therefore, only a single beam could be monitored at any given time. The system alignment is detailed in the next section.

5.4.2 System alignment

Pictures of the transmitter and receiver implementations are given in Figure 65 (a) and (b). The transmitters' ref path and the receiver alignments have been already discussed in Chapter 3 for PtoP communications.

The demux path though requires a different alignment. A WDM beam (2 channels) is incident on a blazed grating. Two beams are diffracted after reflection creating an angle β between them as shown in Figure 65 (a). The value of β depends on the WDM channel spectral distance $\Delta\lambda_{ch}$, and the angle of incidence on the blazed grating. For the setup $\Delta\lambda_{ch} = 1600 - 1550 = 50$ nm and the

angle of incidence was set close to 28° to match the blazed angle given in the datasheet. Then, a pair of mirrors separates the diffracted beam further as β is small ($\beta < 1^\circ$). Finally, an additional pair of mirrors is used to create two parallel beams incident on the $\sim 7 \times 7 \text{ mm}^2$ SLM active area. The beams' footprint in the SLM plane is sketched in Figure 61 (a)). The two beams reflected from the SLM enter the AM, and after angular magnification propagate in free space.

5.4.3 Free space beam diffraction

The free space link after the transmitter AM is a narrow beam. The corresponding beam-spreading under propagation (diffraction effect) is a major contributor to the overall link loss, as studied in section 3.4.1. This beam spreading varies with the effective beam illumination profile on the Tx SLM.

To quantify this effect, an InGaAs digital camera was placed at $Z = 0.5 \text{ m}$ from the BS transmitter output. The steering was performed at low link angles to avoid aberration effects from the AM. The camera images are shown in Figure 66 for the different configurations. For the three PtoM tests, the output beam divergence was increased compared to the PtoP reference beam width. The

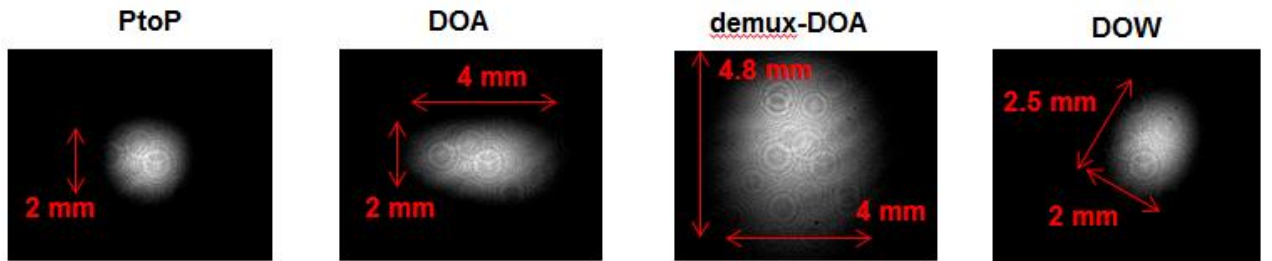


Figure 66. Beam profiles after 0.5 m propagation from the transmitter. The DOA and DOW tests use a beam illumination on the SLM of 7 mm in diameter. The demux-DOA uses a 3.5 mm beam diameter for illumination.

DOW beamsteering showed the smallest increase due to the absence of an aperture division. The beams generated using DOA increased their divergence by a factor of 2 in the direction where the amplitude division took place. For the demux- DOA, the use of beams with half the diameter increased the divergence by at least a factor of 2. These results are consistent with the narrow beam propagation theory and experimental work studied in section 3.4.1. That is, according to equation (19) if the width of a beam is reduced by X in a given direction, the beam divergence is expected to increase by X in the same direction.

5.4.4 Power coupling experiment

The test bed was simplified to a 2-beam PtoM experiment. The three tests introduced in section 5.3 were used. For each test, the first beam was steered to a fixed angle θ_l . The transmitted optical power in this direction was monitored using the NT receiver shown in Figure 64. Simultaneously, the second beam was randomly steered within the $\pm 30^\circ$ FOV cone (100 random steering angles were chosen). This way the movement of a secondary NT was emulated, whilst the static NT was aligned to the BS's steering angle θ_l .

The results are shown in Figure 67. The red line with squared symbols gives the PtoP performance using the ref path configuration, i.e. a large 7 mm diameter beam illuminating the SLM and no spatial division of the SLM. For the DOA configuration two curves labelled 'left' and 'right' were plotted denoting the area of the SLM whose beam was being monitored (the same applied to the demux-DOA configuration). The DOW test was represented by just one curve as the two generated beams are indistinguishable from the SLM illumination point of view.

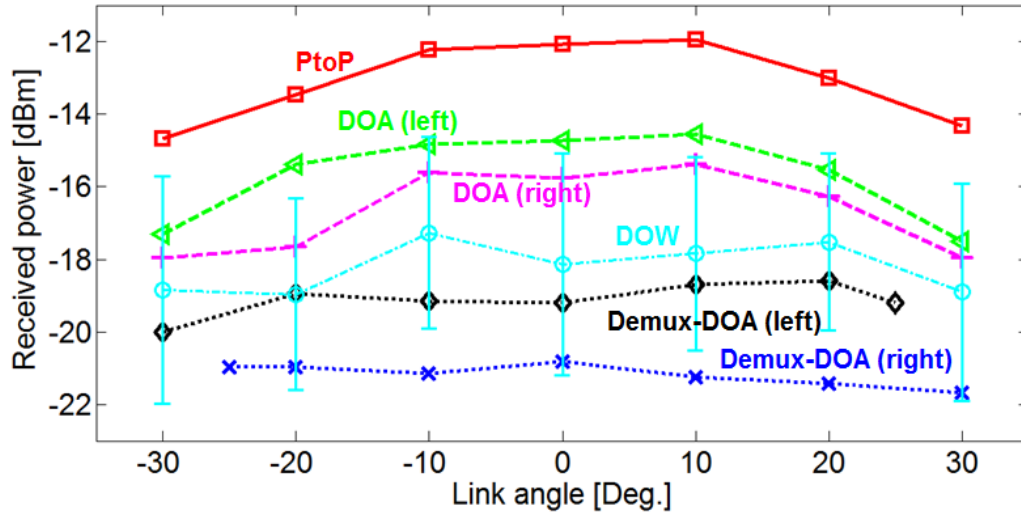


Figure 67. Received power coupled into a fibre-based NT as a function of the transmitter's link angle θ_l . The transmitter output power is 10 dBm for all measurements. The NT is aligned to the incoming beam direction. The tags left / right refers to the area of the SLM whose beam is being monitored.

It can be seen that all PtoM schemes gave coupling penalties of at least 3 dB compared to the PtoP case. The DOA showed the best power coupling efficiency amongst the three PtoM tests. The DOW curve suffered from power coupling fluctuations due to the hologram generation being a function of both the monitored and the randomly steered beams. In contrast, there was no noticeable power coupling fluctuation for the DOA configurations as the diffraction gratings are independently generated for each beam.

However, the DOA principle is not a scalable solution. By increasing the number of sectors to $N \times N$, the beam divergence due to diffraction will increase N times. In principle, the DOW generation does not have this limitation as the number of beams is increased. Figure 68 shows the experimental generation of a 9×9 array of steered beams (the distortions in the corners of the

image are due to defocus aberration of the imaging optics). This large array of spots would be difficult to realize using the DOA tests.

5.4.5 Hologram generation time and adaptive optics

The hologram generation time was also studied for a 512×512 matrix corresponding to the SLM pixelated hologram plane. The DOA tests used diffraction gratings whereas the DOW required the GS iterative algorithm at a relatively high computational cost. Both hologram methods were executed on a GeForce GTX 750 Ti GPU manufactured by Nvidia. This GPU contains 640 cores running at 1020MHz. The Matlab Parallel Computing Toolbox was also used to program the device. The measured generation time was 3.5 ms and 56.2 ms for the diffraction grating and GS hologram, respectively. This estimation included the hologram transfer from the GPU to the computer RAM memory. It can be concluded that the diffraction grating generation is more than 10 times faster than the GS algorithm. In future real-time implementations, the GS algorithm will

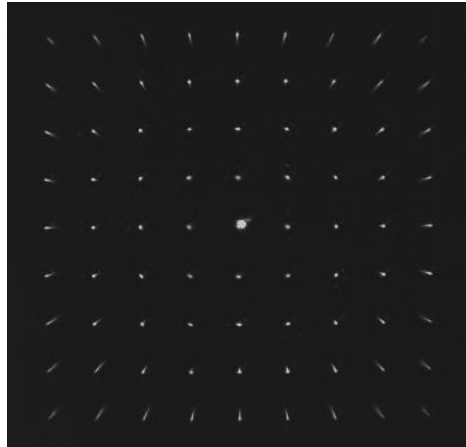


Figure 68. Pictures of the target reciprocal plane captured by an analogue InGaAs camera. A GS generated hologram was programmed on the SLM to experimentally obtained a 9×9 array of points.

have to be used with some form of hologram storage module and look-up table software.

Besides the default beamsteering holograms, adaptive optics phase profiles can be programmed in the SLM to compensate for aberrations (see section 3.4.1). For the DOA tests, the aberration correction function can be tailored to each individual beam in the spatially divided SLM. However, the DOW does not have this capability because all beams originally overlap in the SLM plane. Therefore, the optimal aberration correction cannot be realised for both beams simultaneously. This effect was not quantified in the experiments as only the monitored beam was optimized to compensate for aberrations.

5.5 COMPARATIVE SUMMARY AND OUTLOOK

Finally, a comparative summary is given in Table 1 for the three tests: demux-DOA, DOA and DOW. No single configuration is optimal in all aspects. A combination of the three tests is envisioned and a given design tailored to the particular application.

As an example, a generalized PtoM distribution system with demux capabilities is shown in Figure 69. For visualization purposes, the schematic is given for 4 sectors / 4 beams incident on the SLM but it can be extended to a larger number of sections. A WDM-PON fibre-source feeds a BS located on the ceiling of an indoor environment. The light is spectrally separated using an arrayed waveguide grating (AWG). The output collimated beams are then directed to the SLM's spatially divided sectors using a mirror array. The mirrors can be oriented such that the zeroth order reflections from the SLM initially address different areas of the room's floor. Finally, each sector can then be independently programmed using the DOA or DOW principles, which adds another degree of beam splitting. This way NTs in close proximity could be addressed as shown with the blue beams in Figure 69.

Table 1. Comparison of PtoM tests

Metric / test	Demux-DOA	DOA	DOW (with GS)
Beam divergence	Large	Medium	Small
Power coupling experiment	Acceptable	Best	Medium
Scalability	Low	Low	High
Hologram generation Time	3.5 ms	3.5 ms	56.2 ms
Adaptive optics capability	Optimal: Independent for all beams	Optimal: Independent for all beams	NOT optimal: shared for all beams

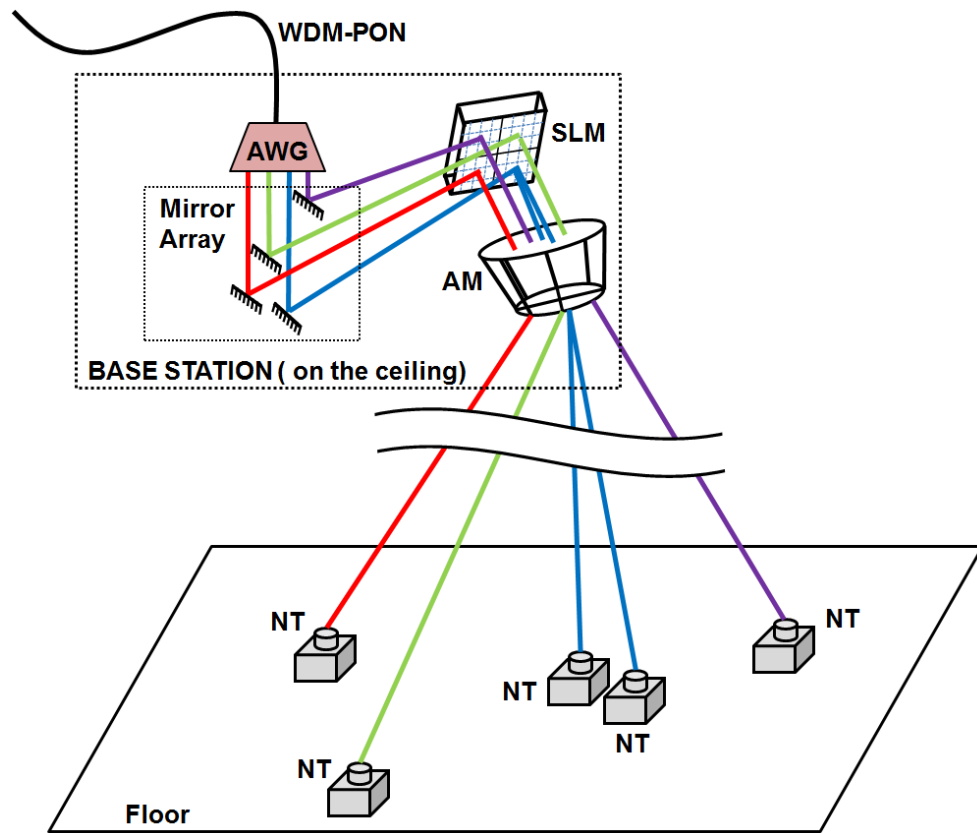


Figure 69. Generalized PtoM distribution system. The coloured beam represent different wavelengths of operation.

Chapter 6

Conclusions and future work

6.1 CONCLUSIONS

This thesis explores the indoor coverage limits of optical wireless communications for mobile applications requiring data rates beyond 100 Gb/s. The motivation is driven by Fibre-to-the-home deployment that can enable Terabit aggregate data rates at the user's doorstep. The concept of an all-optical network is proposed, spanning over both the fibre and wireless domains to effectively deliver sub-Terabit data rates to nomadic users in indoor scenarios. This is challenging to wireless technologies, as these systems typically handle data rates orders of magnitudes below the fibre capacities. To bridge this gap, an ultrafast transparent and bidirectional fibre-wireless-fibre (FWF) link with aggregate data rates exceeding 400 Gb/s was successfully designed and implemented. Although FWF geometries for wireless communications had been studied before, a practical room-scale coverage of such links is shown here for the first time.

To accomplish this, a system defined by a fixed base station (BS) on the ceiling and several nomadic terminals (NTs) arbitrarily located throughout the room was presented. The BS was fed via a fibre backbone whose function is to distribute the aggregate data rate capacities over the different NTs. Following the downlink link path, the infrared light exiting the fibre was first divided into multiple eye-safe narrow beams. Assuming a line-of-sight, these eye-safe beams were then directed to the NT locations using some form of beamsteering. Due to the inherent link bi-directionality and the use of fibre-based receivers, a similar beamsteering unit was required at the NT.

From the architecture definition the following challenging problems were defined:

- (i) The design of wireless units for the FWF link ends capable of efficient and accurate beamsteering to / from fibre-based transceivers with a wide coverage.
- (ii) The optimization of the coverage whilst maintaining a feasible communications link for ultrafast wireless applications greater than 100 Gb/s.
- (iii) The development of a localization and tracking system to automatically align the FWF link over the optimized coverage.
- (iv) The generation of multiple beams capabilities at the BS to achieve point-to-multipoint indoor communications.

Chapter 2 addressed problem (i). A survey of non-mechanical beamsteering technologies capable of delivering dynamic and accurate beamsteering was carried out. Spatial light modulators (SLMs) were chosen as a mature holographic beamsteering method capable of multiple beam generation and adaptive optics.

Chapter 3 focused on problems (i) and (ii). A symmetric FWF model was first developed to understand the link budget using identical SMF-based transceivers. The link FOV was obtained via a combination of active SLM beamsteering and passive angular magnification (AM). For narrow beam wireless communications, a major trade-off was found between the link FOV (θ_{FOV}) and the active beamsteering capability.

In this chapter, laboratory experiments also demonstrated a symmetric FWF link with a wide FOV of $\theta_{FOV} = \pm 30^\circ$. This allowed for an indoor coverage area of 3.4 m in diameter at a range of 3 m. For this scenario, a communications link operating at 209 Gb/s using a state-of-the-art WDM

coherent transmission system was reported. A reduced FOV of $\theta_{FOV} = \pm 20^\circ$ allowed for an enhanced data rate of 418 Gb/s. To the best of our knowledge, this is the fastest demonstration of an indoor wireless link that offers practical room-scale coverage. These results were undertaken in UCL's Optical Network Group lab facilities. The coherent WDM transmission system was designed and controlled by UCL collaborators. My contribution was focused on the FWF link and its integration to the transmission system.

Chapter 4 addressed problem (iii) by designing and demonstrating a suitable automated alignment system for a FWF link with a $\theta_{FOV} = \pm 30^\circ$ at a range of $Z = 2.8\text{ m}$. The integration of a CMOS camera-based localization system at the BS and a quadrant-photodetector tracking at the NT allowed for automated link alignment. The achieved response time of the order of seconds is compatible with nomadic rather than mobile applications. A localization accuracy of 0.05° (2.5 mm pointing accuracy at 3 m) was achieved. This demonstration showed it is feasible to use an automated system to achieve the required alignment for an ultra-high data rate FWF link.

Finally, Chapter 5 dealt with the point-to-multipoint problem defined in (iv). A 2-beam generation case was experimentally characterized. The beamsteering power coupling performance was measured with a fibre-based receiver aligned to one of the emitted beams. The results showed that spatial division of the SLM into independently programmable areas (division of amplitude principle) is a good approach for a few-beam generation. The approach used simple diffraction gratings on the SLM with fast programming times. However, the solution is not scalable as the number of NTs increases. More complex hologram generation methods making use of the division of wavefront principle may be needed at the expenses of higher computational costs.

In summary, the potential of wide FOV SMF-wireless-SMF links to break the data rate limits of indoor optical wireless communications has been shown. A record data rate link of 418 Gb/s and 209 Gb/s at a FOV of $\pm 30^\circ$ and $\pm 20^\circ$, respectively, was reported at a free space transceiver's distance of 3 m. The optical link was eye safe and a state-of-the-art coherent WDM transmission system was used. As the system design was transparent and bidirectional, higher data rates and simpler transmission schemes are possible. Additionally, an automated localization and tracking was successfully developed for the link alignment as well as the point-to-multipoint capabilities of an SLM-based BS.

6.2 FUTURE WORK

Future work may include the demonstration of FWF links with cost effective beamsteering components and multimode fibres. The coherent transmission system can also be simplified to intensity modulation direct detection (IM-DD) schemes. At the same time, the NT terminals with fibre-based transceivers can be modified into free-space detectors. The design of the uplink as well as the reduction of the link budget will be challenging problems in these simplified architectures. Additionally, new beamsteering systems such as electrowetting components can also be tested in optical wireless communication applications. A more matured technology would be needed to find commercial components with good beamsteering performance and amicable interfaces. Photo refractive devices could also be further explored if new materials with sensitivities in the infrared are discovered.

As of the automated link alignment, work should focus on faster implementations of the CMOS camera and image processing for the BS localization system. The NT tracking module currently

using quadrant photo-detectors may also be enhanced by using position sensing detectors with relative independence of the beam intensity profile.

The demonstration of point-to-multipoint communications with the simultaneous transmission experiment over two or more nomadic terminals is also desirable. The design and implementation of an indoor fibre-access point acting as wireless distribution system for WDM applications is attractive. In this system, a WDM passive optical network feeds a BS and the multi-channel link is de-multiplexed using dispersive elements. The separated WDM channels become independent free space beams, which are then directed to NTs distributed over the room.

Finally, this research can serve as guidance for future design of optical indoor cellular network. In this thesis, a single BS distribution point was studied for a given room. Practical coverage limitations were seen as the link capacity was increased. Optical cellular networks could extend coverage by replicating several cells such as the one studied here, without sacrificing the link capacity. However, careful attention would have to be paid to eye-safety, particularly at the cells' boundaries where multiple beams from different BS access points may overlap.

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