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Free Space Optical Communications with Multi-Beam Laser Terminals for Satellites: Design Insights and Applications

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ABSTRACT

Traditional laser communication terminals are limited to point-to-point links, which constrains their scalability and flexibility for global networks that require simultaneous connections with multiple targets. While multiple single-beam terminals can expand capacity, this approach multiplies Size, Weight, Power, and Cost (SWaPC), limiting scalability. Multi-beam laser communication terminals offer a promising alternative, though the design of an effective beam steering system remains a key challenge. This paper explores the design process of such a system, providing an overview of multi-beam steering literature as well as an comparison and trade-off of existing space-borne multi-beam steering technologies. It also analyzes insights from related fields such as terrestrial laser communications, LiFi, single-beam laser communication, optical cross-connects, radio links, and multiple target tracking. Key system functions are identified and visualized in a function flow diagram, and various design options are evaluated, culminating in a design options tree which serves as a design recipe. Two application scenarios, involving high and low target densities, demonstrate that steering systems based on micro-mirror arrays and spatial light modulators present significant advantages over alternatives. This study offers a comprehensive framework for designing multi-beam steering systems for space-based laser communication terminals.

Keywords: Multi-Beam Laser Communication, FSOC, Spatial Light Modulators

1. INTRODUCTION

Ever increasing demand for unfettered high speed global access to data has lead to data and network providers to seek ways to meet this demand. However, in order to affordably connect the most remote and difficult to reach customers, a new approach is needed. Furthermore, constructing physical infrastructure can be costly, inflexible and vulnerable to outages.[1–7] A strong contender is providing wireless networks from space. Numerous large satellite constellations are currently being designed or are under construction, primarily using radio communication. The problem, however, are radio capacity limitations.[5,8]

A promising alternative technology already in use to speed op data transmission would be laser communication. Due to micro-meter wavelengths instead of millimeter radio wavelengths the beam divergence can be reduced by at least 3 orders of magnitude for a given aperture size. As a result, the transmission losses are heavily reduced and cross talk between users eliminated, making available a comparatively large bandwidth at high signal to noise ratios (SNR). This allows for higher capacity data links at lower SWaP, making laser communications an attractive technology for space based communications.[5,6]

As a result, although not yet equally as established as radio communications, laser communications are seeing increased use in space. For example, bringing laser communication to consumers on the ground, air and sea is also gaining interest.[1–4,9–11] Furthermore, as small satellites are becoming increasingly numerous[5,12] in various applications, laser communication promises miniaturized high capacity communication for small satellites.[5,6] In this vein, large satellite constellations heavily rely on small satellites[5,8,12] to bring internet connection to consumers from space, and require increased capacity between satellites to facilitate this.[13] Furthermore, large capacity feeder links[3] and data relay applications[14–16] are also looking for laser communications to supplement the download of data between space and ground.

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These trends indicate a direction of space based laser communications to be used in all aspects of communications, especially in networks. The domains of these communications span a wide range of locations, from LEO to GEO and large networks to single links. Of particular interest in this work are applications where laser communication is expected to serve numerous clients. Specifically in the area of space-to-space and space-to-earth communications, with the former focusing on inter satellite data relay/forwarding applications and the latter on providing data services to numerous users on Earth.

Nonetheless, low beam divergence simultaneously also makes laser communication by nature point-to-point communication. Although this might be sufficient for some applications, it might hold back integration of laser communication into point-to-multi-point applications.[17,18]

It is difficult if not impossible to predict exactly what will encourage or hold back the application of laser communication in the future. There are 3 overlapping potential areas identified where laser communication for space applications see challenges: link switching and reliability, routing of data and nodal networks, and scalability in terms of Size, Weight and Power (SWaP) when expanding to multiple links per satellite.

Link switching for example, is where the link needs to be established with a different transceiver. Switching links is inevitable when targets and transceivers are moving into or out of each others view. As a result of low beam divergence and optical wavelengths, moving in and out of view completely interrupts data flow for a significant portion of time until the next link is finally established.[9,10,19–21] This makes the (re-)acquisition phase inherently expensive as it requires peer discovery through thorough searching the field of regard (FoR). When optimizing links though cost functions, a large cost is attributed to termination and (re-)acquisition processes for establishing a new link.[9,10,20–22] As a result of this cost, the decision to switch to more optimal links is postponed thereby decreasing the attractiveness of using laser communication. This has been subject to optimization as well.[9,20–22]

Connecting points to multiple other points though links naturally creates nodal networks, where each node is connected to multiple other nodes. This not only allows for redundancy and flexibility in routing options but also increased volumes of data transmitted though multiple links. Furthermore, these network architectures are commonly used and would improve compatibility with existing network architectures and routing algorithms, further improving performance.[8,17–19,23–27] The drawback of laser communication being point-to-point by nature, it connects 2 nodes instead of one to multiple. Proposed laser communication networks rely on multiple laser communication terminals per spacecraft to create these networks as a result.[17,18,24,25,28–30]

Considering the scalability of such a solution, while increasing the number of terminals would work to make spacecraft point-to-multi-point, it does not reduce the SWaP per beam. The result is limited scalability of laser communication in such applications. This is in stark contrast to modern radio communication systems, which has the ability for to perform communications over multiple links at once.[17,18,24,25,28–30]

As a result, combining multiple beams into in a single multi-beam terminal (MBT) would go a long way to over come the 3 challenging areas mentioned above. This would allow establishment of links to multiple unique targets while sharing components, making it more SWaP friendly per beam and therefore more scalable.[24,28–30] Multiple links to multiple targets, such as shown in Figure 1, would also create a nodal network and there by providing multiple routing options. Another benefit is that each terminal has a set of existing optimized links, allowing interruption of multiple links at once while not losing connection to the wider network which improves reliability. The terminal would also be able to acquire new links in parallel to maintaining the existing links, in turn cutting the cost of (re-)acquisition.

Some work on space MBTs for space applications have been done, and will be investigated in greater detail in subsection 3.1. However, the available literature is sparse. Nevertheless, some work has been done on the design of multi-beam steering systems, proposing systems from antenna and mirror arrays on overview papers.[24,30] Work has been done on FSM array designs which use multiple FSMs to steer multiple beams.[31,32] Furthermore, a design has been proposed where transceivers are selected to spatially serve an area.[33] However, these systems are not described in detail beyond their patents.

More detailed work has been done on the use of liquid lenses to create multi-user laser communication. Such a system use a wide beam steering concept and quickly jumps between targets to establish and maintain multiple links at once.[34] While this concept is interesting, the time division of a single beam of such a system

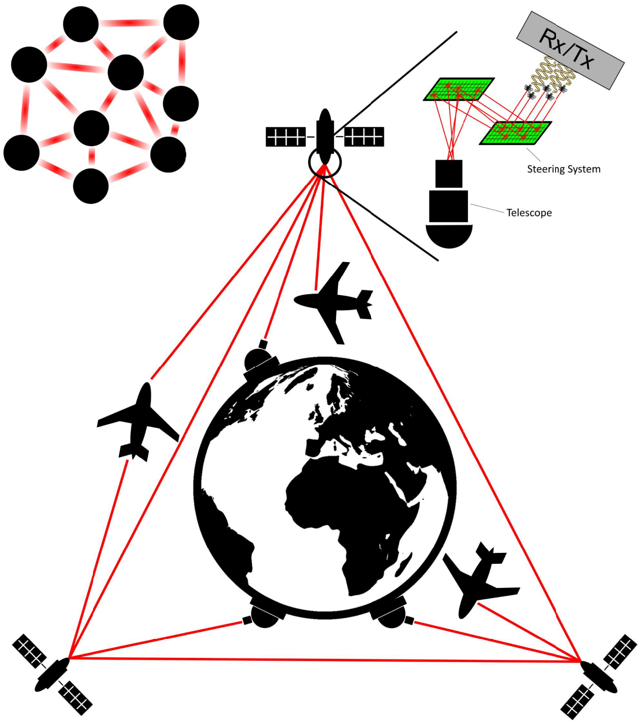


Figure 1. Illustration of multi-beam laser communication terminals in space providing data connection services to a variety of users in a nodal network type fashion.

is not within the scope of this work. Other work which considers sustained multiple beams on multi-staged steering systems combining multiple steering mechanisms have also been proposed. This would improve the flexibility and scalability of such a terminal.[28] Perhaps a system which has been furthest developed, is One-Point to Multi-Point laser communication system (OPMP), which has been designed,[17,18,25,35] prototyped and experimented.[17,18] This design features large mirror arrays arranged in a specific configurations to allow for a large field of service.

As can be seen, the work on space borne MBTs is somewhat limited and are therefore still in their infancy.[17,18,24] The existing work also consists of a number of very different design choices resulting in stark differences between designs. As a result, there is currently a framework lacking through which the design of MBTs, specifically the steering portion, can be thought about. Such a framework could be created by analyzing the use cases, adjacent fields, added value and important functions of MBTs. This helps create an overview of possible design options and layouts for the multi-beam steering system.

In this paper we propose a function flow diagram and design option tree for MBTs to help answer the question:

How can multi-beam steering systems be designed?

This question will be answered in 2 parts by answering the following: 1) What are the functions that an MBT steering system needs to fulfill? 2) What are the design options and how can we select between them?

Subsequently, the results from these sections will be applied to some selected use cases and the outcomes discussed.

2. FUNCTIONS OF MULTI-BEAM LASER COMMUNICATION TERMINALS

This section will discuss the functions of a multi-beam laser communication terminal (MBT) steering system. Taking a page from single beam laser communication terminals, the function flow of MBTs is split into 3 parts:

1) Acquisition. 2) Link sustainment. 3) Link termination. Considering that MBTs have multiple links, the functions can be viewed from both a per-link perspective as well as the functions of the terminal as a whole. All of these will be discussed in their own subsections, starting with acquisition.

2.1 Acquisition

In this text acquisition is understood to be the process of establishing a link. Due to the low beam divergences used in laser communication, finding the target on its own can be difficult and time consuming.[9, 10, 19–21] Not many proposed acquisition schemes for MBTs have been found by the author. Hence the functions here are extrapolated from 3 adjacent areas: 1) single beam laser communication terminals (SBTs) 2) multi-beam radio communication 3) multiple target tracking.

Considering SBTs first, a challenge that MBTs share with SBTs is that the narrow beam width creates a problem in determining the location of the other terminal, especially without prior knowledge. This is overcome through search patterns. These search patterns can be initiated by either party and often are shaped as a spiral. Each terminal monitors its Field of Regard (FoR) for a signal from the other. This pattern is then expanded until such a signal is received. The target is then tracked and steered to until pointing errors have been reduced such that communication becomes possible. This is often achieved through through both coarse as well as fine steering. Once the signal is coupled into the transceiver, communication can begin and the acquisition phase is over.[36–41]

The main take aways from SBTs would be that the narrow beam divergence is overcome through following a search pattern and monitoring of the FoR for return signals, in the same way as SBTs. However, when investigated, the single beam acquisition process differs in 2 main ways from multi-beam acquisition. The first is the size, orientation and use of the FoR and the need to accommodate multiple beams in multiple stages at the same time. The second is the need to filter out noise and false targets. To determine the associated functions, radio and multiple target tracking was used.

To communicate with multiple spatially distributed targets in a reliable manner, it is likely the orientation of the terminal and by extent the FoR cannot be easily adjusted. As a result, the FoR tracking sensor of an MBT is likely larger compared to that of an SBT. The identified literature on proposed MBT designs also have this all in common.

Multi-beam radio communication, such as that found for 5G and 4G, acquire spatially through detection on an antenna array with a large FoR. This is done without adjusting the orientation of the array it self. The FoR plane is therefor spatially sampled by transmitters and receivers. Transmitters are then selected to optimally serve the new target while maintaining the existing links.[42–46]

For radio communications, techniques to sub-divide the plane and strategically tile are directly transferable to MBTs which tile the plane and steer beams using transmitter selection. For MBTs which require steering, these methods are still useful when utilizing the FoR for steering and receiving purposes. Missing however, is a method by which multiple targets can be correctly identified and tracked in the presence of noise. Furthermore, the steering system in such systems will not be able to rely on transceiver selection.

Tracking multiple targets in the presence of noise is a problem that has been extensively studied for applications such as aircraft tracking. Detailed analysis of multiple target tracking and multiple beam steering for multi-beam laser communication will both be subject of future publications. However, in short, there is a need to filter the sensor data and subsequently validate as well as identify the target. In multiple target tracking, the sensor read out and data processing is separated from the data analysis to assess likelihood of correct target identification. During this process the potential new target is tracked and evaluated through a probabilistic approach. In the mean time, each existing target is also tracked simultaneously without interruption.[47, 48] Each MBT which requires target tracking for both active steering or transmitter selection.

Taking the literature into account, it is now needed to adapt this to MBTs. From the perspective of one beam within the MBT, the functions have been illustrated in a function flow diagram shown in Figure 2. In the grander scheme of things, when considering multiple beams, the multiple target tracking algorithm will be able to assess all existing and potential new beams in the FoR at once. The same is true for the steering algorithm which will consider the placement of any newly acquired beams to assign receivers and transmitters as required.

The operation of an MBT, in contrast with a SBT, exists on a continuum. Where multiple links at once are acquired, communicated over and transmitted at the same time. This will be discussed later in subsection 2.4.

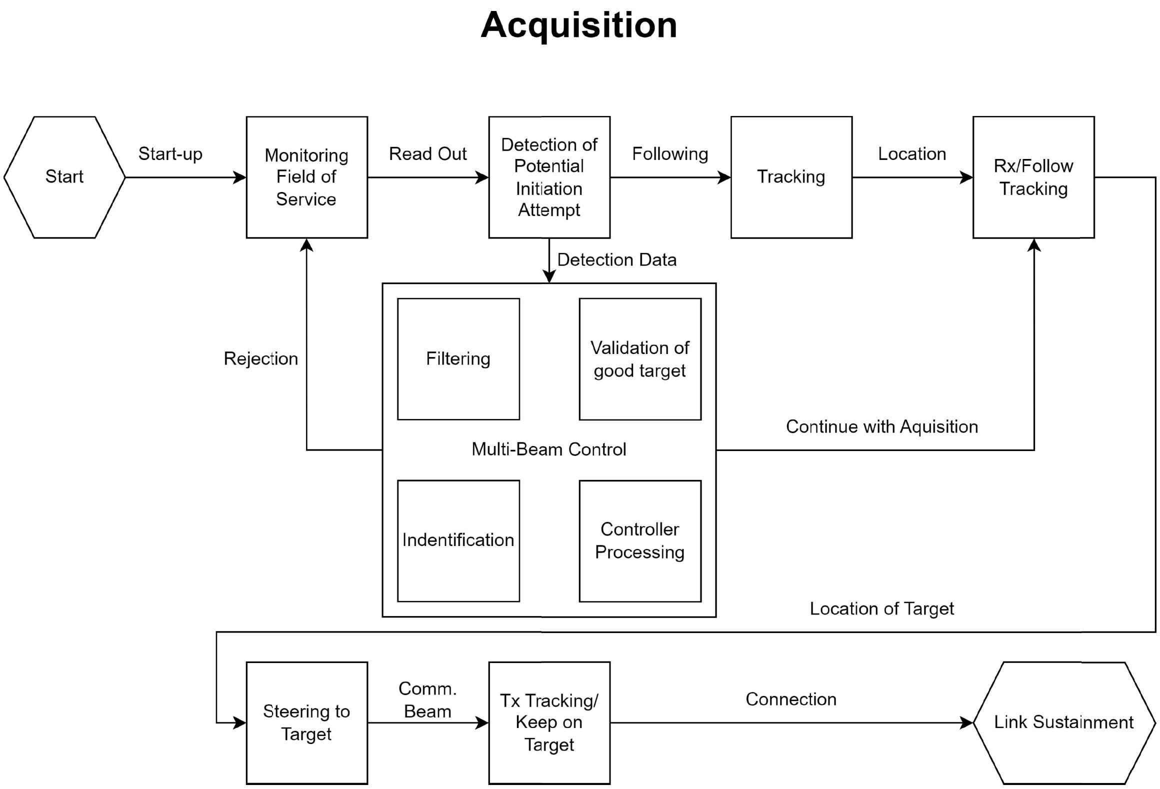


Figure 2. Function flow diagram of multi-beam acquisition.

After acquisition, the processes needed to sustain a link are initiated.

2.2 Link Sustainment Functions

In this text link sustainment is understood to be the process by which a link is maintained such that data can be transmitted. From the perspective of the terminal when considering one beam, it chronologically occurs after acquisition. However, from the broader terminal perspective, it is a portion of the link life cycle which multiple links could continuously enter, exist and leave at once.

As with SBTs, phenomena such as jitter and target motion should be compensated. SBTs do so through tracking the beam and correcting for errors. The wandering motion of the target can be compensated through coarse pointing systems or body pointing. For MBTs however, as discussed in subsection 2.1, the FoR must accommodate multiple targets and as a result might not be re-orientable to a more favorable position. As a result the FoR will likely be larger to accommodate this wander and spatial distribution of targets.

For some radio systems which tile the FoR with beams, due to more divergent preformed beams and static antennas, tend to hand over the target to the next beam or slew a beam.[42–46] This process can be referred to as pre-coding. In the case of MBTs where transmitters and receivers are selected as a form of steering, this approach would be similar.

With respect to multiple target tracking, the main functions of filtering and target identification remain relevant. One key component is to temporally maintain the correct label to each beam from one instant of time to the next. This is particularly important when beams are in the proximity to other beams as these are regions where confusion can most likely occur.[47,48] However, there are numerous and diverse method through which this can be done, and this is beyond the scope of this paper.

One thing to note is that the transmitted beam and the received beams can be considered separate, unless the terminal is designed such that the control of one directly controls the other. The function flow for link sustainment from the perspective of a terminal of one beam is shown in Figure 3.

This diagram in form looks most similar to that of an SBT. However, when diving into more detail of each function, the implementation can take inspiration from radio and multiple target tracking.

2.3 Link Termination Functions

When the link either is lost, a hand off needs to occur or the communication has ended, the link can ended through termination process.

In the case of multi-beam radio communications as well as multiple target tracking, a form of register is maintained of the known targets and their location.[47,48] Such data needs to be updated. In the case of abrupt loss of contact an analysis needs to be performed to see if the beam has indeed been lost. This is illustrated in Figure 4.

2.4 Multi-Beam Terminal Functions

Until now the functions have been viewed from the perspective of the terminal on the life cycle of one beam. From a broader perspective, the terminal is handling multiple beams in various stages at once. In contrast to SBTs, MBTs operate on a continuum of link acquisition, sustainment and subsequent termination, as shown in Figure 5. From a global perspective, these functions need to happen in a parallel and coordinated fashion to achieve high quality and reliable links. Furthermore, it is important from an MBT perspective that the different targets are kept separate from each other, in particular when it comes to control. This is done through filtering and correct identification as part of multiple target tracking in combination with a steering strategy shown in Figure 6.

3. DESIGN OPTIONS FOR MULTI-BEAM STEERING SYSTEMS

Now that the functions of multi-beam steering have been discussed, the design of the steering system can now be investigated. When designing an multi-beam steering system, two questions arise: 1) what are the plausible design options? and 2) how can we select between them?

To answer these questions, the approach is split into 4 parts: 1) An overview of the high level design choices made by other MBT designs, both for spacecraft as well as terrestrial applications. 2) A possible design decision tree is presented which can be followed as a recipe for a specific use case. 3) Some use cases have been selected and the tree is then applied to these. 4) The results of this section are discussed.

For this paper we shall stay at a high level, as the more detailed design is likely dependent on the specific requirements at hand.

3.1 Previous Multi-Beam Steering System Designs

In this subsection we will gather design choices based on previous literature on MBTs. Although the available literature on space borne MBT terminal design is limited, it is still valuable to consider what has been done before. The goal is to determine what designs are commonly used in which context. However, in order to overcome the lack of literature, designs from adjacent fields which contain systems with overlap of space MBTs have also been selected. In total 20 systems were selected from space MBTs, 3D MEMS optical cross connects (OXC), Lifi, and fixed multiple input and multiple output (MIMO) free space laser communication systems. This list is by no means exhaustive, however was selected to give an impression on the kinds of systems out there. It is also noted that each design can be made unique in subtle ways, hence a more coarse and high level approach was chosen. For a visual reference and representation of steering systems, please see Figure 7.

The functions discussed in section 2 fall in 3 categories: 1) Steering beams. 2) Sensing beams. 3) Filtering and controlling beams. These functions need to be designed for specifically based on the expected encountered use case scenarios. System architecture and design for steering, tracking, filtering and controlling beams depend on the communication method, target behavior, density and communication direction.

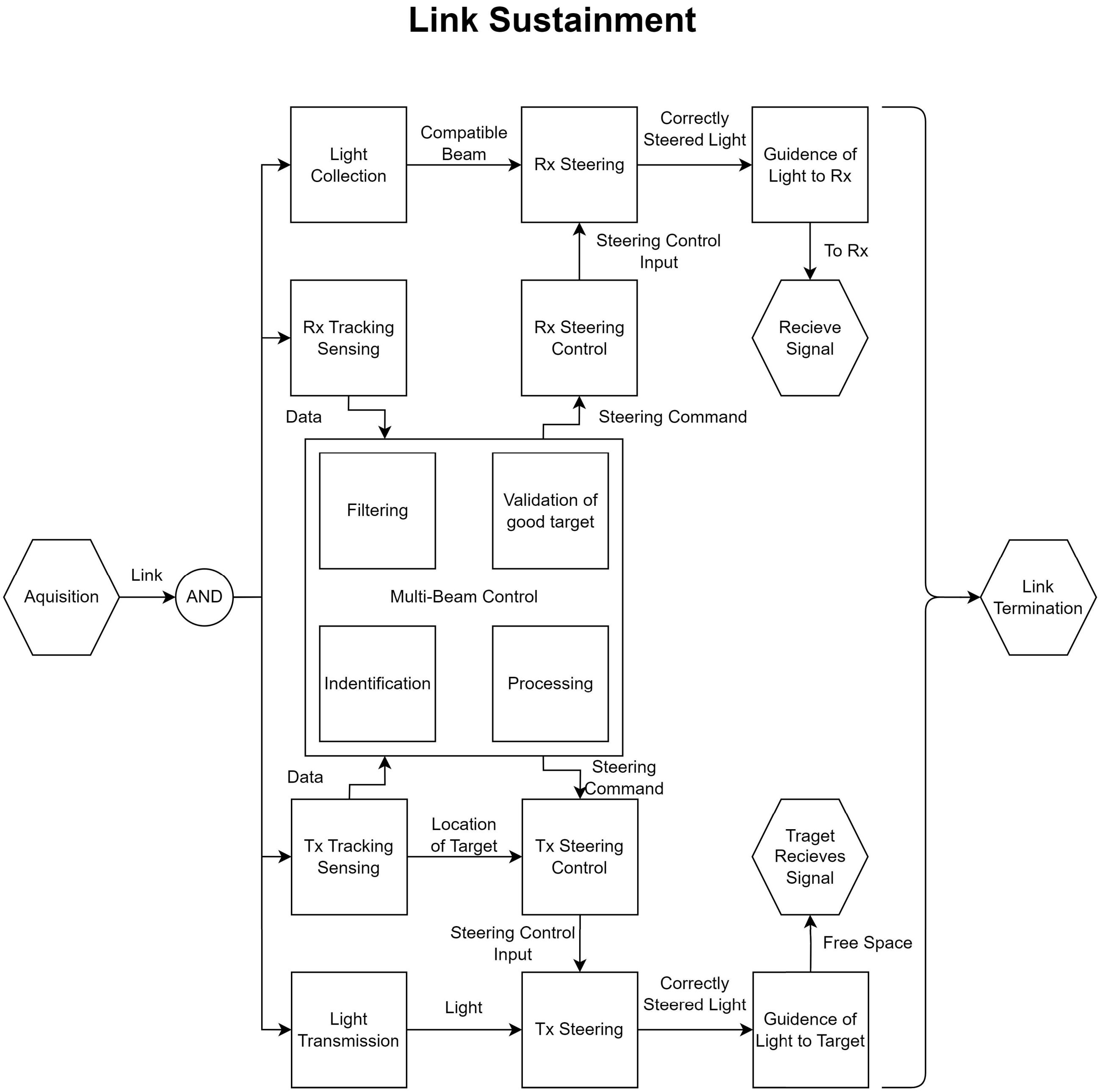


Figure 3. Function flow diagram of multi-beam link sustainment.

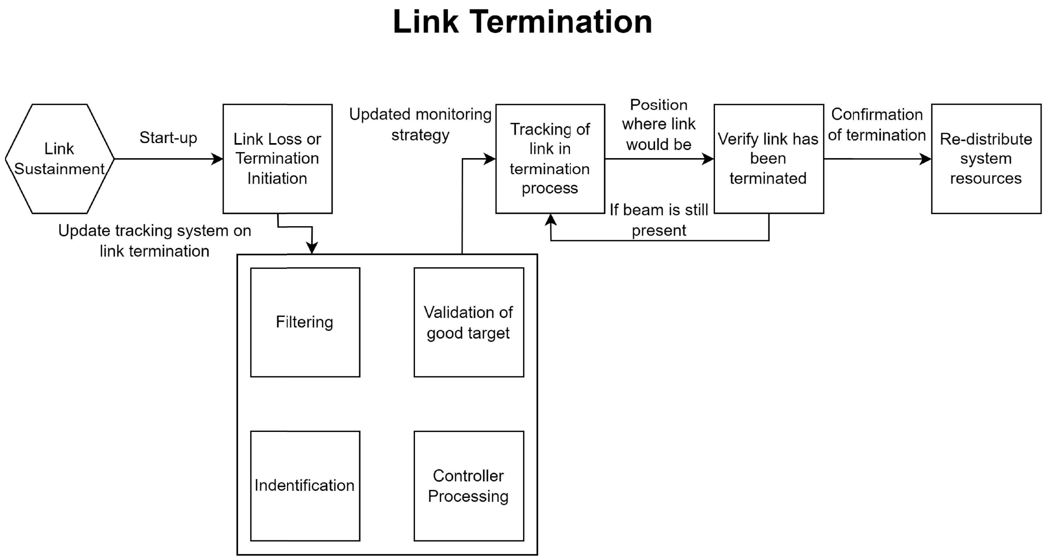


Figure 4. Function flow diagram of link termination.

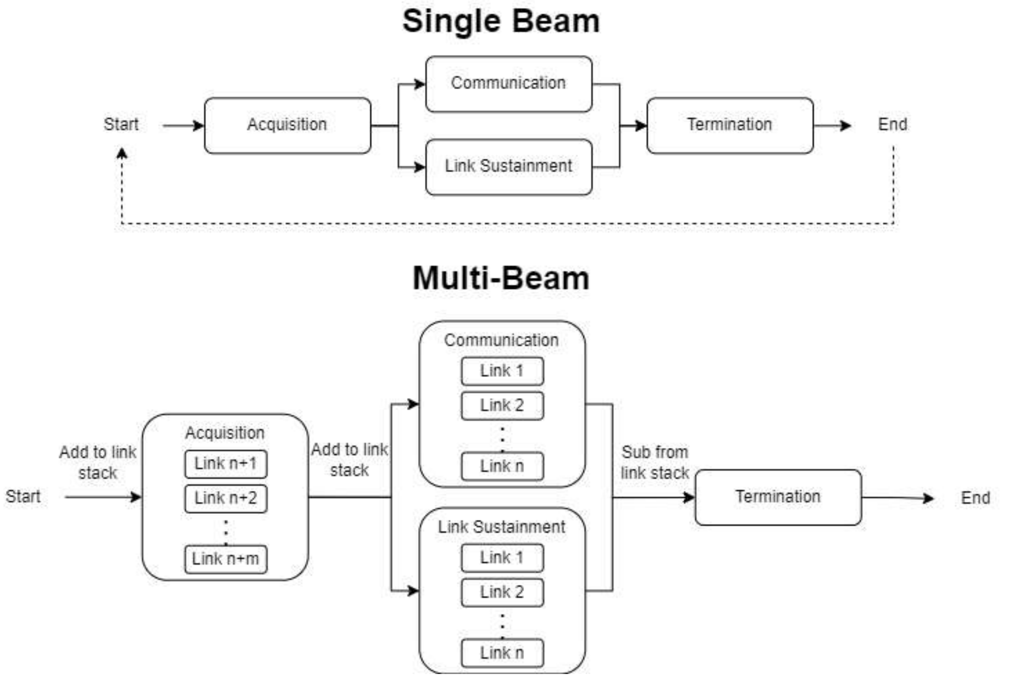


Figure 5. Phases of beams from perspective of single and multi-beam terminals.

In order to derive a set of design choices, it was chosen to compare these characteristics derived from the functions to the application to the design choices. This was broken down into 4 categories, each with 2 juxtaposing subcategories: 1) Transmission: broadcasting and point-to-point. 2) Target behavior: Static vs moving targets. 3) Target density with respect to steering system spatial resolution: higher or lower. 4) Communication direction: duplex or non-duplex.

In the same vein, the designs aspects where split into 3 main design choices: 1) Steering mechanism. 2) Type of steering control loop employed. 3) Number of steering stages. It was found that when a different combination of these design choices were chosen it would drive the design into a different direction. Furthermore, these design

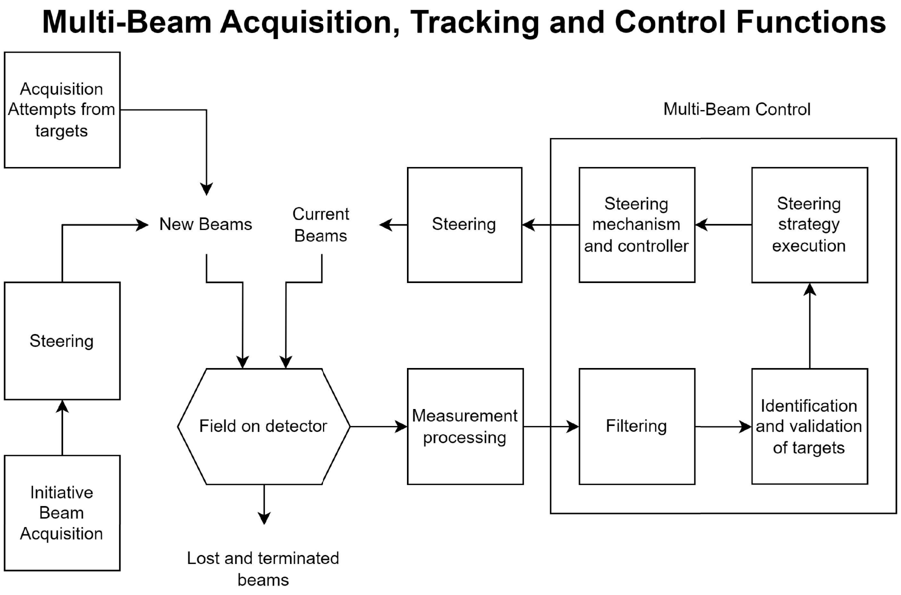


Figure 6. High level function flow for a multi-beam steering system.

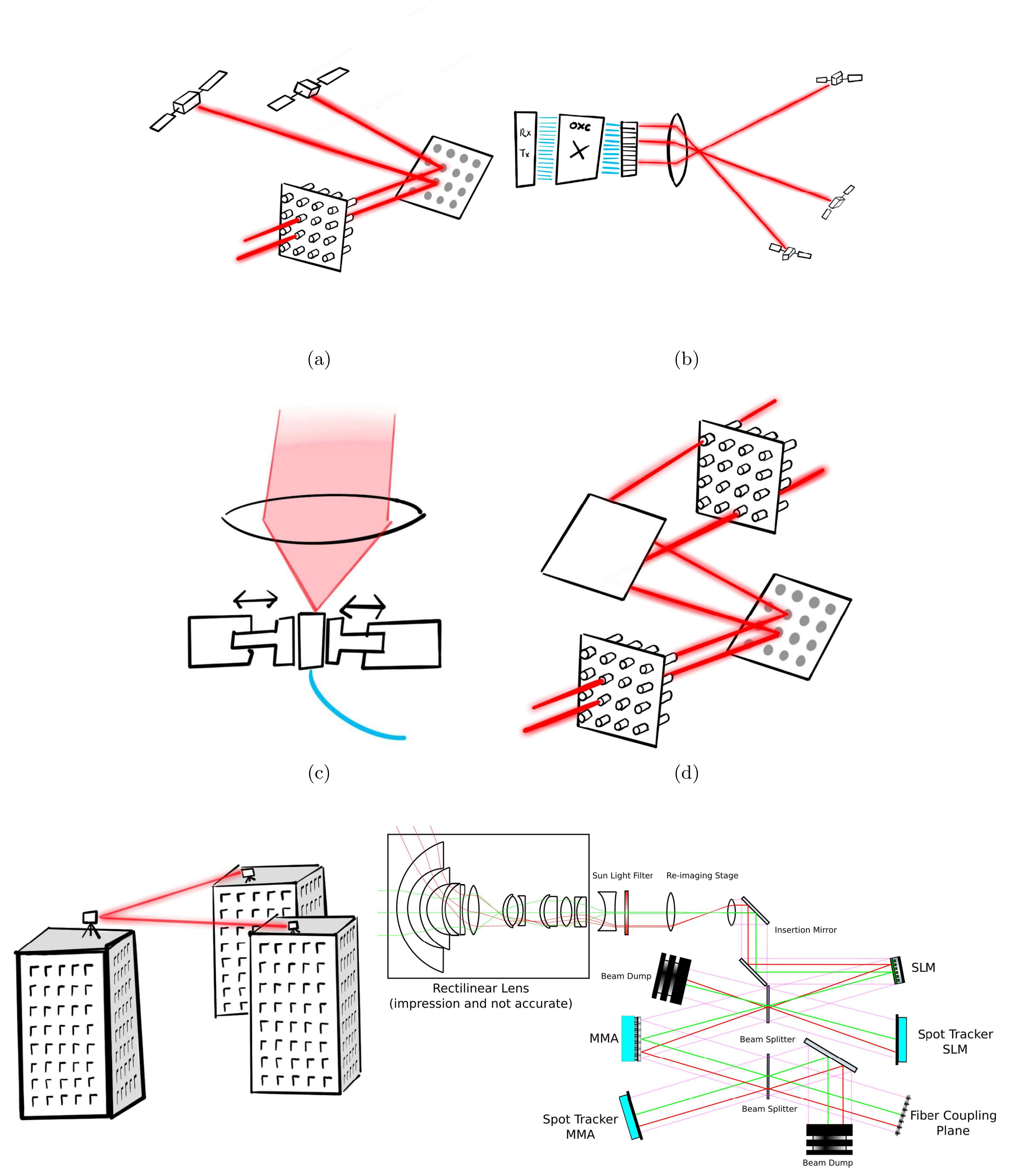
aspects can be used in high level system design and traded-off to select the best solution for a given use case.

To see an overview of the 20 systems and their design choices, a complete table can be found in Table 4, with Table 5 serving as index. However, to make the discussion more clear and improve the digestibility of the literature tables, a color coded version in accordance with their nominal use case environment are provided in Table 1 with the index presented in Table 2.

What can be seen from Table 1(a) is the breath of design choices which are being made for space MBTs spans most of the table. Nevertheless, within the space MBTs considered in this list the most common design choice was to use a form of mirrors in a closed control loop. However a number opt for transciever selection. First, in order to gain insight into the design choices, we will compare these terminals with applications such as LiFi, fixed point-to-multi-point systems and optical switches (OXC) to gain insight.

Comparing OXCs to space MBTs a number of interesting overlaps in Table 1(b) can be observed. For one, the OXCs considered for this paper use 3D MEMS micro mirror arrays (MMA) to connect one optic fiber to another one. These tend to use 2 steering stages to control the angle and position of arrival of the beam into the target fiber, increasing efficiency through reduction of insertion losses (in this case analogous to fiber coupling efficiency).[49–53] Furthermore, since both the optic fibers are static, each optic fiber on either end of the steering system has a dedicated micro-mirror. These MMAs are selected for their switch speed and their ability to connect any 2 fibers through a combination of 2 mirrors. This makes it possible to cross connect on the order of 1000x1000 fibers in a compact form factor, demonstrating the scalability of such a steering system.[49–56] Since each fiber has a dedicated mirror, the beams are both of a smaller diameter than the mirrors and the target density must be smaller than the steering resolution. Lastly, since the locations of each fiber is known, the control loop used is open and no tracking sensors are required. This in turn saves signal power due to no beam splitter being needed to feed light into a tracking sensor and there by improving overall system efficiency.

While some space applications might use an open control loop for transceiver selection, when using mirrors this is likely not the case. This is primarily due to the targets not being static and the need to compensate the target wander as well as the spacecraft jitter. This likely makes the transferability of the control aspects are limited. On the other hand the improvement in fiber coupling efficiency when using multi-stage control could be considered when improving the system efficiency. Spaander[28] proposes an SLM-MMA multi-stage steering system, using the SLM to correct for target wander and an MMA for higher speed disturbance compensation. This has the added benefit of reducing the number of beams to track, as the transmitted and received beams



(a) (b)

(c) (d)

(e) (f)

Figure 7. Examples of multi-beam steering systems. (a) Illustrates an FSM and large mirror arrays. (b) Illustrates a transceiver selection system. (c) Illustration of transceiver positioning. (d) Illustration of 3D MEMS switch. (e) Illustration of fixed MIMO system. (f) Illustration of a multi-staged multi-beam steering system. Figure taken from "Free-Space Multi-beam Optical Communication Terminal Design for Spacecraft" by J. Spaander on page 81 Figure 5.32,[28] reprinted with permission.

(a) Space terminals

Application\Design Choice	Transmitter selection	Large Mirrors (B<M)	FSMs and MMAs (B<M)	MMAs and SLMs (B>M)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point		🟦	🟦	🟦	🟦	🟦		🟦	🟦	
Static tragets										
Moving targets		🟦	🟦	🟦	🟦	🟦		🟦	🟦	
Target density greater than steering system resolution										
Target density smaller than steering system resolution		🟦	🟦	🟦	🟦	🟦		🟦	🟦	
Duplex		🟦	🟦	🟦	🟦	🟦		🟦	🟦	
Non-dupex		🟦	🟦		🟦	🟦		🟦	🟦	

(b) Space terminals compared to 3D MEMS optical cross switches

Application\Design Choice	Transmitter selection	Large Mirrors (B<M)	FSMs and MMAs (B<M)	MMAs and SLMs (B>M)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point		🟦	▨	🟦	🟦	▨		▨	🟦	
Static tragets			🟨			🟨		🟨		
Moving targets		🟦	🟦	🟦	🟦	🟦		🟦	🟦	
Target density greater than steering system resolution										
Target density smaller than steering system resolution		🟦	▨	🟦	🟦	▨		▨	🟦	
Duplex		🟦	▨	🟦	🟦	▨		▨	🟦	
Non-dupex		🟦	🟦		🟦	🟦		🟦	🟦	

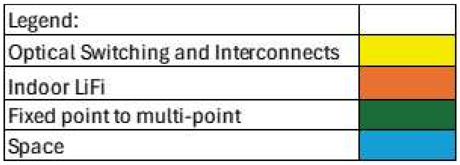
(c) Space terminals compared to indoor LiFi terminals

Application\Design Choice	Transmitter selection	Large Mirrors (B<M)	FSMs and MMAs (B<M)	MMAs and SLMs (B>M)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point	🟧	🟦	🟦	🟦	🟦	🟦	🟧	🟦	🟦	🟧
Static tragets	🟧						🟧			🟧
Moving targets		🟦	🟦	🟦	🟦	🟦		🟦	🟦	
Target density greater than steering system resolution	🟧						🟧			🟧
Target density smaller than steering system resolution		🟦	🟦	🟦	🟦	🟦		🟦	🟦	
Duplex		🟦	🟦	🟦	🟦	🟦		🟦	🟦	
Non-dupex	🟧	🟦	🟦		🟦	🟦	🟧	🟦	🟦	🟧

(d) Space terminals compared to fixed point t multi-point terminals

Application\Design Choice	Transmitter selection	Large Mirrors (B<M)	FSMs and MMAs (B<M)	MMAs and SLMs (B>M)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point		▨	🟦	🟦	▨	▨		▨	▨	
Static tragets		🟩			🟩	🟩		🟩	🟩	
Moving targets		🟦	🟦	🟦	🟦	🟦		🟦	🟦	
Target density greater than steering system resolution										
Target density smaller than steering system resolution		▨	🟦	🟦	▨	▨		▨	▨	
Duplex		▨	🟦	🟦	▨	▨		▨	▨	
Non-dupex		▨	🟦		▨	▨		▨	▨	

Table 1. Literature Comparison Tables, see Table 2 for the index. ”B” and ”M” denote beam and mirror sizes respectively.



Legend:	
Optical Switching and Interconnects	🟨
Indoor LiFi	🟧
Fixed point to multi-point	🟩
Space	🟦

Table 2. Index for Table 1.

follow the same path due control position as well as incident angle degrees of freedom. In this case, signal power efficiency is reduced due to the additional tracking sensor. A system with a similar control scheme is proposed by Mitchell et. al.[57] to compensate for jitter, howevet this is used for a single beam.

When considering Table 1(c) it shows limited overlap between the selected LiFi systems and space MBT as the concepts used are more similar to lanterns. However, this approach is similar to transceiver selection and taken as a method to make a compact system without moving components. Furthermore, the wider beams also allow for users to move throughout the FoR without the need for high spatial resolution in both steering and tracking. As a result, the target density can be larger than the steering resolution.

Lastly, observing Table 1(d), fixed point-to-multi-point systems used, for example, to communicate between buildings or server racks have significant overlap. Often these systems require closed loop control to compensate for jitter, as is the case for space applications. However, the beam propagation regime is over distances short enough that beam divergence is not as significant of an issue. In combination with considerably less strict SWaP requirements, this allows fixed point-to-multi-point systems to use mirrors larger than the beam diameters. However, these proposed systems are free space multi-beam laser communication terminals used for MIMO network applications.

Also important to note, no system considered used light to broadcast information over the whole aperture. While not directly motivated in literature, it can be speculated that this has not been done due to it removing the main benefit of optical communication, namely low beam divergences.

Coming back to space MBTs, it is clear that closed control loops are preferred due to target motion and jitter. However, when considering design choices for steering mechanisms mirrors and transceiver selection are most popular. Although these design choices are not fully justified, it does seem that these systems intend to simplify the system by removing control loops and moving components. Nevertheless, creating a duplex system where the received beam is passively coupled into the receiver is a difficult task which requires high densities of receivers to cover the FoR and numerous hand-offs during the link sustainment phase.

Having considered the state of the art of previous MBT steering system designs, subsection 3.2 will combine these design choices. The combined design options is combined with a proposed method to chose between them.

3.2 Design Options and Recipe

Having evaluated the design choices made by previous designs in subsection 3.1, an overview of design options can be created. However, the design choices discussed in subsection 3.1 have not been motivated in writing/literature directly from a detailed analysis of SWaP or performance. It is difficult to find exact dimensions, mass and power consumption data as well as an analysis and motivation why. As a result, comparing these on that level of detail is beyond the scope of this paper. However, the design choices can be compared from a perspective of practicality. This section will investigate and propose a method on making choices between the design options at this preliminary stage.

As such, a design recipe in the form of a design option tree is proposed in Figure 8. This tree can be used by answering simple yes or no questions based on the use case selected.

Considering Figure 8 and reflecting back to the design choices discussed in subsection 3.1 and the functions in section 2, there is a pattern that can be recognized. The first step is not chosen often, as shown in Table 1, since this would negate the beam divergence benefits of optical wavelengths.

Having selected point-to-point communication, the question of the motion of the targets need to be answered. In some applications, such as between two formation flying satellites and internal laser communication,

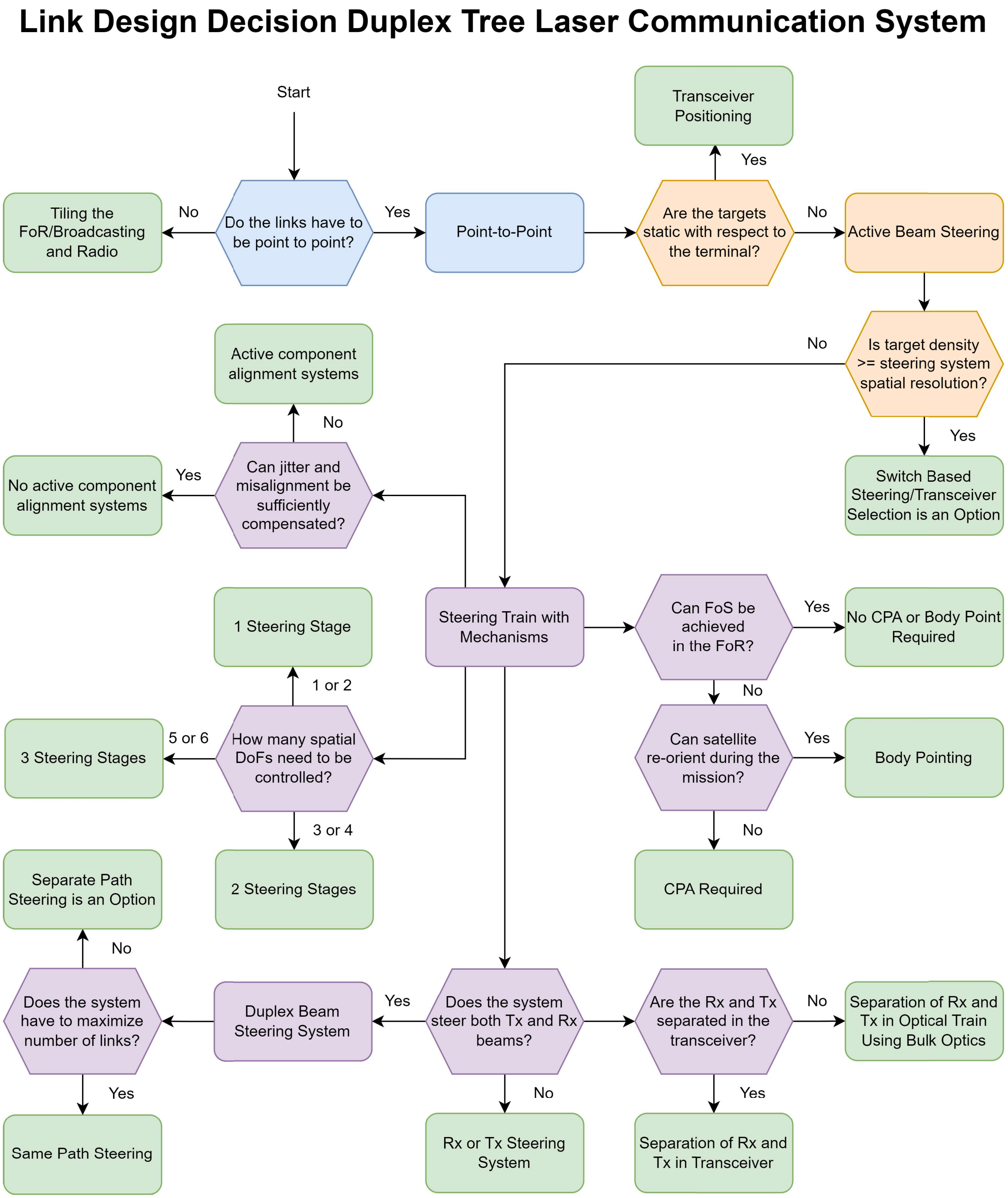


Figure 8. Design options tree.

considering the targets static might be a valid assumption. Placing the terminals statically would reduce the system complexity substantially. However, for inter-satellite and space-to-ground communication as discussed in section 1, this is not a valid assumption.

The target density in these applications could be higher than the steering spatial resolution. As a result, distinguishing and serving the targets individually through the steering system might not be possible. This would imply that transceiver selection could be possible design choice due to the discretization of the field of service not being problematic. In fact, choosing this option could be advantageous as it would not require any moving components on the optical side and reduce the steering system complexity. However, when communicating with resolvable targets which need to be served individually, this might be an issue.

What is left are steering mechanisms. Due to the diversity on available mechanisms and the amount of available research, this part of the tree is more detailed. Moving clockwise, the question of the need for a coarse pointing assembly (CPA) can be answered by whether or not the field of service can be achieved in the field of regard. Should this not be the case and the satellite cannot reorient during the mission, then a CPA would be required.

The transceiver type will influence the geometry of the steering system. Hence, a bulk optics or fiber based transceiver would influence this. Furthermore, the need for a duplex system will influence the choice on the need to simultaneously steer beams in multiple directions. This would make the steering system more complex. Lastly, the number of beams required to be tracked can be halved if the Rx and Tx beams share the same path. As a result, only the one set of beams needs to be tracked, simplifying the system. On top of this, the system also becomes more signal power efficient not having to track as many beams.

As discussed in subsection 3.1, multiple steering stages allow control over more degrees of freedom (DoFs), which in turn can reduce insertion losses. A single steering stage and influence the spot position, however not the angle of arrival i.e. 2 degrees of freedom. Increasing the number to 2 steering stages allows also control over the angle of arrival along 2 axes, increasing the control able degrees of freedom to 4. Also changing the rotation and/or delay of the beam, which might be required in polarization sensitive applications for example, another stage is needed to rotate the beam along its axes.

Lastly, should the jitter not be sufficiently compensated for, then active alignment of the transceivers could be an option. However, the added complexity of such a measure needs to be subject of a trade-off.

Considering the design options, a choice needs to be made as to which type of steering mechanism/technology would suit the application best. The next section will discuss the possible trade-offs of such a choice and present some of the considerations.

3.3 Steering Mechanism Selection

Having applied the design options tree, the resulting design might require a steering mechanism which can steer multiple beams. The primary function of a steering mechanism is to actively control and change the direction of the beams, thereby spatially mapping the FoR to the transceiver plane. However, ideally the mechanism should also be able to perform this function continuously for the duration the target is actively wanting to communicate within the FoR. This is both a function of this ability to continuously steer the beam during beam wander as well as the density of targets it is capable of handling just to name a few considerations.

Provided there are numerous options to chose from with various criteria, a selection of the options was narrowed down and investigated based off the systems in subsection 3.1. In order to help compare steering mechanisms, Table 3 was created to provide a holistic view the possible options and their strengths. A trade-off table for steering mechanisms was chosen because it provides a structured way to evaluate and compare the various design options based on multiple performance criteria. Table 3 is not complete, criteria such as cost are left out. This is done due to the high variability in cost between components and a thorough cost analysis being beyond the scope of this paper. More over, weights have not be attributed.

The criteria chosen and their are as follows:

Multi-Beam Steering Mechansim Trade-Off Table

Steering Mechanism	Micro-Mirror SLM	Liquid Crystal SLM	MMA > Beam Diameter	FSM array with mirror > beam diameter	Large mirror array with mirror > beam diameter	Transciever selection
Continous Rx beam steering during wander	No loss of signal when beam wanders.	No loss of signal when beam wanders.	Beam wander must remain on the mirror.	Beam wander must remain on the mirror.	Beam wander must remain on the mirror.	Beam wander must remain on the mirror.
Diffraction	Diffraction is inherent but dependent on specific device.	Diffraction is inherent but dependent on specific device.	When on the mirror there is no diffraction.	When on the mirror there is no diffraction.	When on the mirror there is no diffraction.	When on the mirror there is no diffraction.
Space heritage	Limited.	Limited.	Limited.	Prominent in space SBTs but not as array.	Large mirrors are prominent in space telescopes and some SBTs.	Limited.
Flexibility and multi-purpose	Re-porgramable to serve any optical functions.	Re-porgramable to serve any optical functions.	Limited to tip-tilt mirror.	Limited to tip-tilt mirror.	Limited to tip-tilt mirror.	Limited to discrete transmission and receiving angles.
Control loop	High resolution devices can be computationally more expensive to control.	High resolution devices can be computationally more expensive to control.	Standard mirror control loop.	Standard mirror control loop.	Standard mirror control loop.	Tracking similar to standard control loops. Steering performed through optical switching.
Allowable proximity between beams	Beams can partially overlap.	Beams can partially overlap.	One mirror diameter.	One mirror diameter.	One mirror diameter.	One transmitter or reciever diameter.
Mass	Low.	Low.	Low.	Medium.	High.	Low.
Polarization limitations	None.	Polarization must align with crystal polarization.	None.	None.	None.	Device dependent.
Wavelength limitations	Mirror actuation range and accuracy dependent on wavelength. Element is dispersive.	Mirror actuation range and accuracy dependent on wavelength. Element is dispersive.	None.	None.	None.	None.

Table 3. Multi-Beam steering mechanism trade-off.

1. **Continuous Rx beam steering during wander** is a criteria where the received beam might be lost when traveling through the FoR. This drop can occur when the beam moves between mirrors, or onto a mirror with another beam already steered. It could also occur when moving between selected receivers.
2. **Diffraction** can occur if the steering mechanism acts as a diffraction grating. Due to diffraction, the light is directed to directions other than the receiver. This can cause losses, cross talk and tracking challenges which need additional design to mitigate. SLMs suffer from diffraction depending on device.
3. **Space heritage** is an important parameter for many spacecraft designer with regards to risk and performance. Particularly within multi-beam laser communication mechanisms considered, there is limited space heritage.

4. **Flexibility and multi-purpose**ness can be offered by a steering mechanism. SLMs for example, can edit the wavefront at high resolutions, allowing for aberration corrections and beam shaping. As a result, a commercial off the shelf device can reduce the number and cost of optical components as well as correct dynamically to new changes in optical performance.
5. **Allowable proximity between beams** is one of the determinants of the allowable target density and proximity. Allowing beams to get closer together would allow for more beams to be accommodated at higher densities. For some devices, such as mirrors larger than the beam diameter, the allowable proximity would be one mirror. For SLMs, the subdiscretization of the beam diameter by pixels allows for the beams to even overlap, making the allowable proximity a function of allowable cross talk and resolvability.
6. **Mass** is an important cost and performance determinant for spacecraft. Larger and heavier systems, such as large mirror arrays, would increase substantially the mass of the spacecraft compared to small and condensed SLMs and MEMS micro-mirror arrays.
7. **Polarization limitations** can be imposed by the steering mechanism, which in turn could make the optical design more complex as well as reduce the multiplexing and modulation options. Liquid crystal SLMs are polarization sensitive in their working and as a result reduces polarization freedom.
8. **Wavelength limitations** similarly impose multiplexing and modulation limitations. SLMs actuators move/delay the wavefront, making the steering wavelength dependent. As a result, for dense wavelength multiplexing, SLMs can still be used. For broader spectra this becomes more difficult as the wavelengths will disperse.

Weights could be attributed to each criteria depending not the specific system requirements. That being said, Table 3 shows a pattern 3 broad categories: 1) beam width being larger than the actuator size, 2) beam width being smaller than the actuator size and 3) transceiver selection. Each category has strengths and weaknesses, what is interesting however is that each category has strengths where others have weaknesses. Therefore, in multi-stage steering, 2 different steering mechanisms from 2 different categories could compliment each other well. Combining these could also lead to the best of both worlds.[28]

Furthermore, an important note on the diffraction effects of SLMs extend further than losses. The diffraction pattern can also cause clutter and interfere with tracking. Methods to reduce the influence of diffraction includes resorting to higher resolution SLMs, improved phase screens and algorithms.[58–64]

In the next subsection, a use case is applied to the methods discussed in previous sections.

3.4 Application on Example Use Cases

To demonstrate the working of Figure 8 and investigate patterns in the design of MBTs, the method is applied to use cases in a quick back of the envelope manner. Hearkening back to section 1, the primary applications of interest for MBTs are facilitating multiple links with non-static targets from space-to-ground or from space-to-space. These are to facilitate ubiquitous global high speed data coverage as well as lower cost per link at higher reliability of connection. As a result, the use cases selected for this subsection are a subset of these use cases.

The space-to-ground applications envisaged in this paper would encompass space-to-air, ground or maritime vehicles as well as fixed stations. The number of users and their unpredictable distribution and motion in the FoR are of interest for scalability and capability. On the other hand, the space-to-space applications envisaged encompass data relay between satellites in a constellation, with a limited number of target satellites in a predictable density.

As a result, 2 axes were identified for the selection of the use case: 1) number of users. 2) Target density. The considered use cases are illustrated on Figure 9.

From the use cases in Figure 9, LEO to Earth based Consumers and Constellation Inter-satellite Data Routing were chosen to chose both ends of the graph.

The functions discussed in subsection 2.1 and subsection 2.2 center around compensating for the motion of numerous non-static targets. Fundamentally, multi-beam systems have sensors with limited spatial resolution

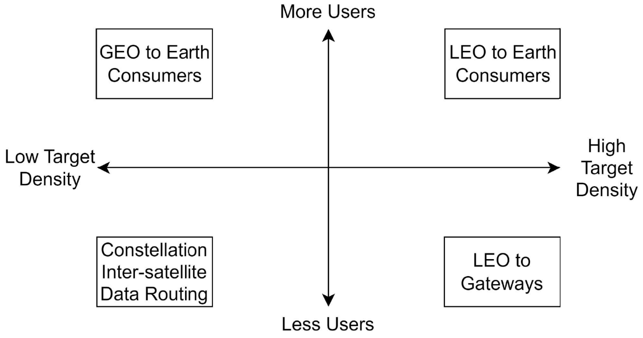


Figure 9. Comparison of use cases on the basis of target wander and number of targets.

when tracking and a limited density/number of actuators on steering mechanisms to steer beams with. However, from the use cases of interest, each target is provided a unique beam. This places the capacity requirements on the tracking and steering mechanism selection.

Combining the above for both use cases, the following are the case:

1. Each link requires point-to-point communication.
2. The targets are not static.
3. The beams are resolvable both for tracking and steering.
4. The field of service falls within the field of regard.
5. The space environment includes jitter, requiring active jitter compensation by the steering system. Active alignment of transceivers though a transceiver alignment mechanism is avoided due to system complexity.

Applying these to Figure 8, both MBTs will use steering mechanisms over transceiver selection/switch based steering. Furthermore, both do not require a CPA and avoid transceiver alignment.

At this stage, the designs of each use case do not significantly diverge. We have found from our own work that most cases result in such a combination. At this stage, what is left is the optical path with respect to the transceivers and decision on the number of steering stages. These are more reliant on specific requirements of the terminal needs to be considered.

From the transceiver side, combining the Rx and Tx into a single transceiver interface could save on steering system complexity. In these systems, fiber based transceivers could be an attractive option as these have small form factors and high performance, attractive for both high target number and data relay applications respectively. Using such a scheme also allows the Rx beam to share the same path as the Tx, reducing the number of beams needed to track for duplex systems (note that this might not be possible for all steering system layouts, some might require multi-stage steering). However, when only considering receiving, the steering requirements could be relaxed when choosing for a larger multi-mode fiber or photo diode.

For the steering stages, the choice between 1 steering stage and 2 steering stages could be based on coupling efficiency, in a similar way 2 steering stages are used for insertion loss reduction in optical switches/cross connects. More steering stages could, for example, be used to de-rotate each beam specifically to the correct orientation of transceiver for polarization sensitive applications. The drawback of increasing the number of steering stages is the increased complexity and increased losses for all the signal power split from the beams needed for each tracking sensor needed. Note that not all steering stage designs require tracking to be performed though beam splitting.

Selecting the steering mechanism and referring to Table 3, for an uninterrupted and geographically ambiguous service from LEO to ground a continuous steering steering capability during beam wander is a necessity.

Furthermore, in this use case the target density could in some places be higher than others. Hence, an SLM would be required to spatially decouple the target from the transceivers. The SLM has the additional benefit of being able to correct for wide angle aberrations and distortions from the telescope, thereby potentially saving on optical components. In subsequent steering stages the beams are already spatially decoupled, hence the translational wander is no longer a problem. At this stage, mirrors could be used, allowing for combining both their strengths.

For data relay within constellations, the target number, density and wander could be determined before hand. Such a system could more easily allow for the targets to be spatially decoupled using a mirror array instead of an SLM. This would allow for more modulation and multiplexing options with regard to wavelength. However, such a choice reduces the steering flexibility and adaptability of this terminal.

3.5 Discussion

Having analyzed the design decisions from previous space MBT designs together with the systems from adjacent fields, a number of design decisions based directly on the use case and trade-offs can be made. From 2 use cases of interest for space MBTs illustrated in this paper, the outcome from the design options tree in Figure 8 is similar. Both designs rely on steering mechanisms to steer beams between the target and transceivers.

This is in contrast to systems which tile the FoR with transceivers, fixed and broadcasting systems due to capacity, link continuity, the vibrational environment and demand for point-to-point communication among other reasons.

Furthermore, the need for spatial decoupling and often dynamic changes in positions and densities of targets, makes mirror arrays with mirrors larger than the beam diameter less attractive for many use cases. As a result, MBT designs for many use cases could benefit from including a steering mechanism where the beam is steered with actuators smaller than the beams them selves, such as micro-mirror array or liquid crystal SLMs.

4. CONCLUSION

In this paper we have looked at the literature, application, functions and design options of multi-beam laser communication terminals (MBTs) steering system for satellites on a high level.

It was found that MBTs could be useful in increasing the connection reliability to a wider network and serve numerous customers. Furthermore, such terminals would add routing options and functionality through a nodal network to laser communication. When accommodating multiple links in one system where components can be shared the cost and SWaP per beam would decrease. This would allow scalability.

The functions of a multi-beam steering system were investigated by evaluating literature on the previous designs of MBTs and by taking a page from adjacent fields of single beam laser communication terminals (SBTs), multi-beam radio systems and multiple target tracking. It was found that there are some common functions all multi-beam steering systems have in common. These revolve around parallel acquisition and sustainment of beams based on monitoring of a wide FoR and a tracking scheme based on probabilistic analysis and verification of the beams being tracked. There are also differences in the functions of the terminal from the perspective of one beam vs all the beams at once. The MBT acquires, maintains and terminates multiple links as once in parallel and as a result operates on a continuum.

Furthermore, the design of the steering system was analyzed on the basis of design options. These design options were sourced from previous space MBTs together with systems of adjacent fields of 3D MEMS optical cross connect switches, indoor LiFi and fixed point-to-multi-point systems. What was found that there is significant overlap between 3D MEMS optical cross connect switches and fixed point-to-multi-point systems. From these a few patterns in design choices were found and these were presented in a design decision tree which can act as a recipe for initial high level design choices depending on the use case. It was applied to 2 use cases of interest for MBTs in different capability and performance regimes. It was found that these resembled each other substantially. Furthermore, due to their ability to continuously steer wandering beams, MEMS micro-mirror array and liquid crystal SLMs are devices which show promise when used as a steering mechanism in at least one steering stage to spatially decouple the target from the field of regard.

Our future work in the coming months will focus on implementation and hardware demonstration of tracking and steering algorithms for a multi-beam steering stage utilizing and SLM.

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APPENDIX A. LITERATURE TABLES

Overview of multi-beam systems found in literature

Application\Design Choice	Transmitter selection	Large Mirrors (B<M)	FSMs and MMAs (B<M)	MMAs and SLMs (B>M)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point	AWGR, VCSEL, COG, DORA	OPMP, OPMPW, SD/TDMAE, IRF	MPFSO, MBLCS, LOXC, LLR, TTMEMS	SLMOIC, MBTS	OPMP, OPMPW, MPFSO, MBLCS, SLMOIC, MBTS, MBLCS2	SD/TDMAE, IRF, LOXC, COG, LLR, TTMEMS	AWGR, VCSEL, DORA	OPMP, OPMPW, MBTS, LOXC, LLR, TTMEMS	SD/TDMAE, IRF, MPFSO, MBLCS, SLMOIC, COG, MBLCS2	AWGR, VCSEL, DORA
Static tragets	AWGR, VCSEL, COG	SD/TDMAE, IRF	LOXC, LLR, TTMEMS	SLMOIC	SLMOIC	SD/TDMAE, IRF, LOXC, COG, LLR, TTMEMS	AWGR, VCSEL	LOXC, LLR, TTMEMS	SD/TDMAE, IRF, MPFSO, MBLCS, SLMOIC, COG	
Moving targets	DORA	OPMP, OPMPW	MPFSO, MBLCS	MBTS	OPMP, OPMPW, MPFSO, MBLCS, MBTS, MBLCS2		DORA	OPMP, OPMPW, MBTS	MBLCS2	DORA
Target density greater than steering system	AWGR, VCSEL, DORA						AWGR, VCSEL, DORA			AWGR, VCSEL, DORA
Target density smaller than steering system resolution	COG	OPMP, OPMPW, SD/TDMAE, IRF	MPFSO, MBLCS, LOXC, LLR, TTMEMS	SLMOIC, MBTS	OPMP, OPMPW, MPFSO, MBLCS, SLMOIC, MBTS, MBLCS2	SD/TDMAE, IRF, LOXC, COG, LLR, TTMEMS		OPMP, OPMPW, MBTS, LOXC, LLR, TTMEMS	SD/TDMAE, IRF, MPFSO, MBLCS, SLMOIC, COG, MBLCS2	
Duplex		OPMP, OPMPW, SD/TDMAE, IRF	MPFSO, MBLCS, LOXC, LLR, TTMEMS	MBTS	OPMP, OPMPW, MPFSO, MBLCS, MBTS, MBLCS2	SD/TDMAE, IRF, LOXC, LLR, TTMEMS		OPMP, OPMPW, MBTS, LOXC, LLR, TTMEMS	SD/TDMAE, IRF, MPFSO, MBLCS, MBLCS2	
Non-dupex	AWGR, VCSEL, COG, DORA			SLMOIC	SLMOIC	COG	AWGR, VCSEL, DORA		SLMOIC, COG	AWGR, VCSEL, DORA

Table 4. Overview of systems placed into design choices table. Table 5 can be used to cross reference which system was selected.

System:	Acronym:	Institution:	References:
One-Point to Multi-Point laser communication system	OPMP	Changchun University	17, 18, 25, 64
SD/TDMA experiment	SD/TDMA E	Graduate School of Global Information and Telecommunication Studies Department of Science Japan Women's University	65
One-Point to Multi-Point laser communication system wedge version	OPMPW	Changchun University	35
FSO link via Intelligent Reflecting Surfaces	IRF	Purvanchal University	66
MULTI - POINT FREE SPACE OPTICAL COMMUNICATION SYSTEM	MPFSO	X Development	31
MULTI-BEAM LASER COMMUNICATIONS SYSTEM AND METHOD	MBLCS	Lockheed Martin Corporation	32
high port count arrayed waveguide grating router (AWGR)	AWGR	TU Eindhoven	67
multiple-input multiple-output (MIMO) optical wireless communication (OWC) link based on vertical cavity surface emitting laser (VCSEL) arrays	VCSEL	University of Strathclyde	68
optical interconnect using a liquid-crystal spatial light modulator	SLMOIC	Cambridge University	59
Multi-Beam laser communication terminal	MBTS	Delft University of Technology	28
large optical cross-connects (OXCs)	LOXC	Lucent Technologies	56
Cognitive multi-user free space optical communication testbed	COG	University of Oklahoma	23
Lucent LambdaRouter	LLR	Lucent Technologies	54
microelectromechanical systems (MEMS) two-axis tilt mirror arrays	TTMEMS	NTT Microsystem Integration Laboratories	51
MULTI-BEAM LASER COMMUNICATIONS SYSTEM AND METHOD	MBLCS2	Lockheed Martin Corporation	33
Deployable Optical Receiver Array Cubesat	DORA	Arizona State University	69

Table 5.