Opinionated article

Alan E. Willner* and Cong Liu

Perspective on using multiple orbital-angular-momentum beams for enhanced capacity in free-space optical communication links

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Abstract: Structured light has gained much interest in increasing communications capacity through the simultaneous transmission of multiple orthogonal beams. This paper gives a perspective on the current state of the art and future challenges, especially with regards to the use of multiple orbital angular momentum modes for system performance enhancement.

Keywords: free-space links; optical communications; optical fibers; orbital angular momentum; space division multiplexing; structured light.

1 Introduction

In 1992, Allen et al. [1] reported that orbital angular momentum (OAM) can be carried by an optical vortex beam. This beam has unique spatial structure, such that the amplitude has a ring-like doughnut profile and the phasefront “twists” in a helical fashion as it propagates. The number of 2π phase changes in the azimuthal direction is the OAM mode order, and beams with different OAM values can be orthogonal to each other. Such structured beams are a subset of the Laguerre–Gaussian (LG_{lp}) modal basis set, which has two modal indices: (1) l represents the number of 2π phase shifts in the azimuthal direction and the size of the ring grows with l; and (2) p+1 represents the number of concentric amplitude rings (see Figure 1) [2]. This orthogonality enables multiple independent optical beams to be multiplexed, spatially copropagate, and be demultiplexed – all with minimal inherent cross talk [3–5].

***Corresponding author: Alan E. Willner,** University of Southern California, Los Angeles, CA, USA, E-mail: willner@usc.edu
Cong Liu, University of Southern California, Los Angeles, CA, USA. https://orcid.org/0000-0003-0089-0763

This orthogonality is of crucial benefit for a communications engineer. It implies that multiple independent data-carrying optical beams can be multiplexed and simultaneously transmitted in either free-space or fiber, thereby multiplying the system data capacity by the total number of beams (see Figure 2). Moreover, since all the beams are in the same frequency band, the system spectral efficiency (i.e., bits/s/Hz) is also increased. These multiplexed orthogonal OAM beams are a form of mode-division multiplexing (MDM), a subset of space-division multiplexing [4–7].

MDM has similarities to wavelength-division multiplexing (WDM), in which multiple independent data-carrying optical beams of different wavelengths can be multiplexed and simultaneously transmitted. WDM revolutionized optical communication systems and is ubiquitously deployed worldwide. Importantly, MDM is generally compatible with and can complement WDM, such that each of many wavelengths can contain many orthogonal structured beams and thus dramatically increase data capacity [8].

The field of OAM-based optical communications: (i) is considered young and rich with scientific and technical challenges, (ii) holds promise for technological advances and applications, and (iii) has produced much research worldwide. Excitingly, the number of publications per year that deal with OAM for communications has grown significantly over the past several years (see Figure 3). Capacities, distances, and number of data channels have all increased [9, 10], and approaches for mitigating degrading effects have produced encouraging results.

A key question remains as to how this young field may develop over the next decade. It is in this spirit that this article is aimed, taking an educated guess as to the subjective and relative merits of different aspects of this field. Specifically, these opinions try to address promising aspects that might be interesting to explore.

As far as context, this article will address a series of short subtopics and present our reasoned opinions. Moreover, due to the nature of this article, references will be

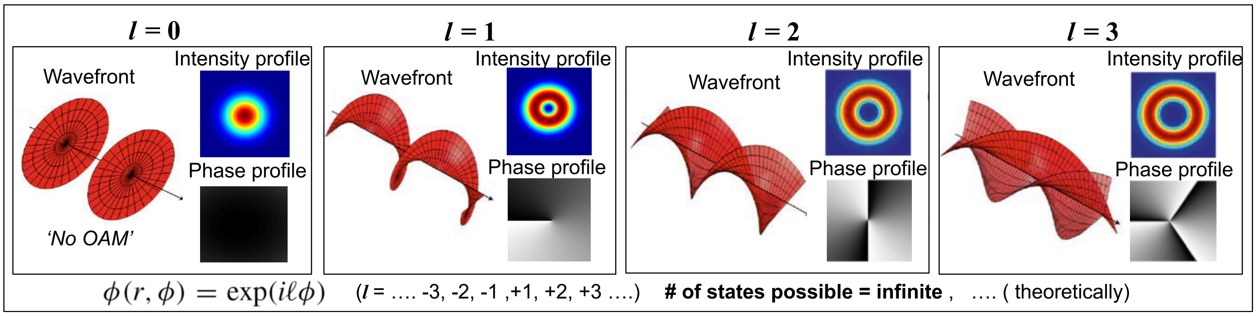

Figure 1: The wavefronts, intensity profiles, and phase profiles of orbital angular momentum (OAM) modes $l = 0, 1, 2$, and 3. The OAM mode with a nonzero order has a donut shape intensity profile and helical phasefront. The size of the ring in the intensity profile grows with l. We note that $p+1$ represents the number of concentric amplitude rings and $p=0$ is shown.

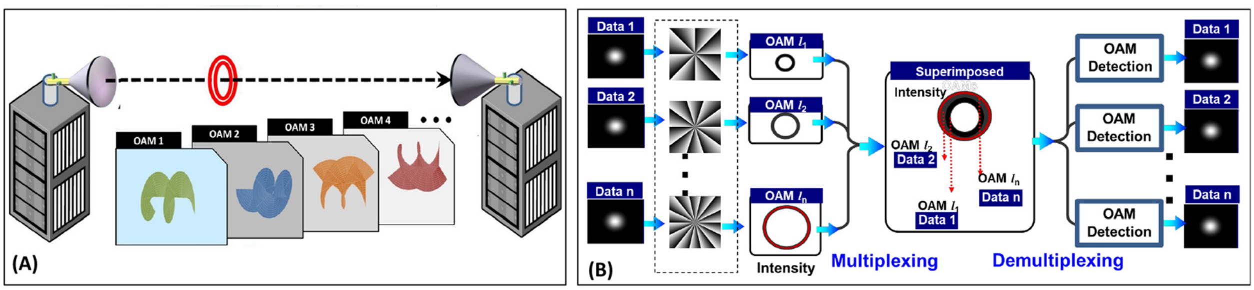

Figure 2: Concept of orbital-angular-momentum (OAM)–multiplexed free-space optical (FSO) links.
(A) Multiple OAM beams are coaxially transmitted through free space. (B) Each orthogonal OAM beam carries an independent data stream.

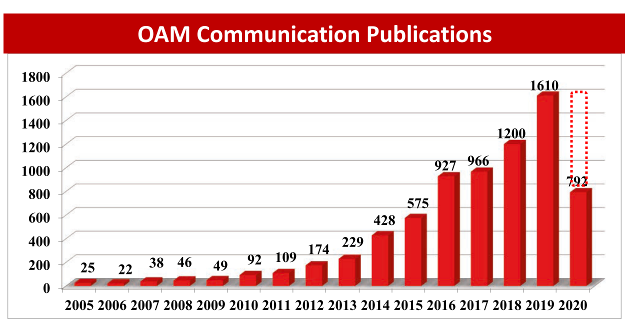

Figure 3: The orbital angular momentum (OAM) communications related publications yearly statistics (until July 2nd, 2020 from Google Scholar, provided by Guodong Xie) [11].

provided for specific background, but the intent is to give a perspective rather than detail. For a basic treatment of OAM-multiplexed communications, the reader is welcome to read A.E. Willner, "Communication With a Twist", *IEEE Spectrum* [12]. Finally and for the sake of readability, the article will generally assume OAM-multiplexed "*free-space classical*" optical communications as the basic default system. Separate subsections will be dedicated to topics that deviate from this system, such as for quantum communications (Section 7) or optical fiber transmission (Section 9).

2 Mitigation of modal coupling and channel crosstalk

A key issue in almost any MDM communication system is dealing with intermodal power coupling and deleterious inter-data-channel crosstalk. There are many causes of modal coupling and crosstalk, including the following for free-space OAM-multiplexed optical communication links:

(a) *Turbulence*: Atmospheric turbulence can cause a phase differential at different cross-sectional locations of a propagating beam. Given this phase change distribution in a changing environment, power can couple from the intended mode into other modes dynamically (e.g., perhaps on the order of milliseconds) [13, 14].

(b) *Misalignment*: Misalignment between the transmitter and receiver means that the receiver aperture is not coaxial with the incoming OAM beams. In order to operate an OAM-multiplexed link, one needs to know the mode that is being transmitted. A receiver aperture that captures power around the center of the beam will recover the full azimuthal phase change and know which l mode was transmitted. However, a limited-size receiver aperture that is off-axis will not recover the full phase change and inadvertently "think" that some power resides in other modes [15].

(c) *Divergence*: Free-space beams of higher OAM orders diverge faster than lower-order beams, thus making it difficult to fully capture the higher-order OAM beam at a limited-sized receiver aperture. Power loss obviously occurs if the beam power is not fully captured, but even modal coupling can occur due to the truncation of the beam's radial profile. This truncation can result in power being coupled to higher-order *p* modes [16, 17].

There are several approaches to potentially mitigate coupling and crosstalk in free-space OAM-multiplexed systems, including (see Figure 4):

(i) *Electrical digital signal processing (DSP)*: Crosstalk due to modal coupling has many similarities to crosstalk that occurs in multiple-transmitter-multiple-receiver (i.e., multiple-input multiple-output, MIMO) radio systems [18]. Multiple optical modes are similar to parallel radio frequency (RF) beams that experience crosstalk. Similar to electronic DSP that can undo much of the crosstalk in MIMO RF systems, these DSP approaches could also be used for mitigating OAM modal crosstalk [19].

(ii) *Adaptive optics*: Adaptive optics, such as by using digital micromirrors, spatial light modulators (SLMs) or multi-plane-light-converters (MPLCs), can mitigate modal crosstalk [20–22]. For example, if atmospheric turbulence causes a certain phase distortion on an optical beam, an SLM at the receiver can induce an inverse phase function to partially undo the effects of turbulence [21]. Typically, there could be a feedback loop, such that a data or probe beam is being monitored for dynamic changes and the new phase function is fed to an SLM.

(iii) *Modifying transmitted beams*: The modal structure of the transmitted beams themselves can be modified. In this approach: (a) the medium is probed by taking power measurements and determining the system modal coupling and channel crosstalk matrix, and (b) transmitting each beam with a combination of modes that represent the "inverse matrix", such that the received data channels would have little crosstalk [23].

Currently, there is an increasing array of potential methods. As with most issues, cost and complexity will play a key role in determining which, if any, mitigating approach should be used.

It should also be mentioned that: (i) modal coupling "tends" to be higher to the adjacent modes, and (ii) separating data channels with a larger modal differential can help in alleviating the problem [14, 24, 25]. Of course, larger modal separation leads to larger beam divergence, so a trade-off analysis is usually recommended.

3 Free-space links

As compared to RF links, optics in general can provide: (a) more bandwidth and higher data capacity due to the higher carrier wave frequency, and (b) better beam directionality and lower divergence, thus making eavesdropping more difficult [15]. When incorporating MDM using OAM multiplexing, such optical links can potentially achieve capacity enhancement and increased difficulty to eavesdropping. This lower probability of intercept stems from the issue that any misalignment causes intermodal coupling, such that it is extremely difficult for an off-axis eavesdropper to recover the signals, and even an on-axis eavesdropper would need to know the modal properties in order to recover the data, again fairly difficult. In addition, these free-space applications share some common desirable characteristics, including: (1) low size, weight and power (SWaP), which can be alleviated by advances in integrated OAM devices [26]; and (2) accurate pointing,

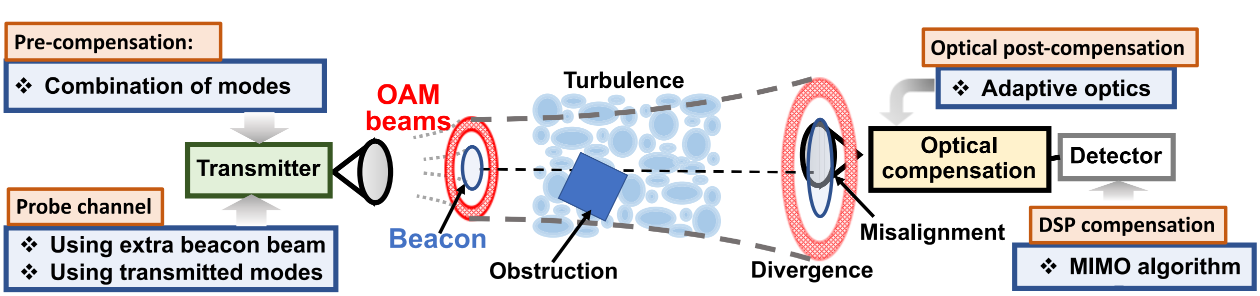

Figure 4: Various crosstalk compensation approaches in orbital-angular-momentum (OAM)–multiplexed links.

acquisition and tracking (PAT) systems, which helps limit modal coupling and crosstalk [15].

These advantages have generated interest in free-space MDM communications in the following scenarios:

(i) *Atmosphere*: OAM multiplexing can potentially benefit communication to: (a) unmanned aerial vehicles, for which distances may be relatively short range and a key challenge is to miniaturize the optical hardware, and (b) airplanes and other flying platforms, for which distances may require turbulence compensation and highly accurate pointing/tracking [27–29] (see Figure 5).

(ii) *Underwater*: Blue–green light has relatively low absorption in water, thereby potentially enabling high-capacity links over ~100 m [30, 31] (see Figure 6). Note that radio waves simply do not propagate well underwater, and common underwater acoustic links have a very low bit rate. For underwater OAM links, challenges include loss, turbidity, scattering, currents, and turbulence. An interesting challenge is transmitting from above water to below the water, such that the structured optical beam would pass through inhomogeneous media surrounding the interface, including nonuniform aerosols above water, the dynamically changing geometry of the air–water interface, and bubbles/surf below the surface.

(iii) *Satellites*: OAM multiplexing may have interesting advantages for up–down links to satellites. However, cross-links that are ultralong might necessitate extremely large apertures due to the increased beam divergence of higher-order modes [32, 33] (see Figure 5).

4 "Why use OAM? Should both modal indices be used?"

(a) *Why use OAM?:* Although there has been significant interest in OAM as a modal basis set for MDM communications, what is the rationale for choosing OAM over other types of modes? On a fundamental level, MDM requires that you can efficiently combine and separate different modes, so almost any complete orthogonal basis set could work. Indeed, many different types of modes were demonstrated in free-space and fiber, including Hermite–Gaussian (HG), LG, and linearly polarized (LP) modes [4–6, 34–37]. In discussions with Robert Boyd and Miles Padgett [38], two practical issues seemed to emerge as to reasons that one "might" prefer OAM modes (as a subset of LG modes) to other modal basis sets:

(i) OAM modes are round, and free-space optical components are readily available in round form.

(ii) It is important to maintain interchannel orthogonality and minimize crosstalk. This can be accomplished by fully capturing the specific parameter that defines the modal orthogonality. For a case in which different channels can be defined by different OAM l values, the channel and mode can be fully determined by azimuthally capturing a full 360° circle no matter the size of the round aperture [39].

(b) *Should both modal indices be used?*: Structured beams that are from a modal basis set can generally be described by two modal indices, such that the beam can be fully described by these coordinates. For example, LG modes have l (azimuthal) and p (radial) components, whereas HG beams have n (horizontal) and m (vertical) components. However, the vast majority of publications concerning MDM-based free-space optical communications utilized only a change in a single modal index for the different OAM beams. Specifically, each beam commonly had a different l value but the same p=0 value [4, 5, 8]. This one-dimensional system can accommodate many

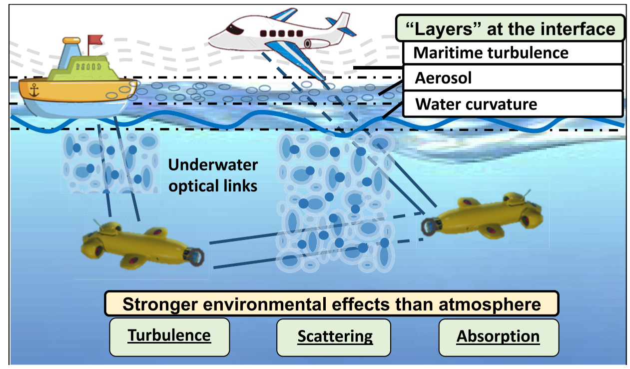

Figure 6: Challenges of different scenarios in underwater free-space optical communications.

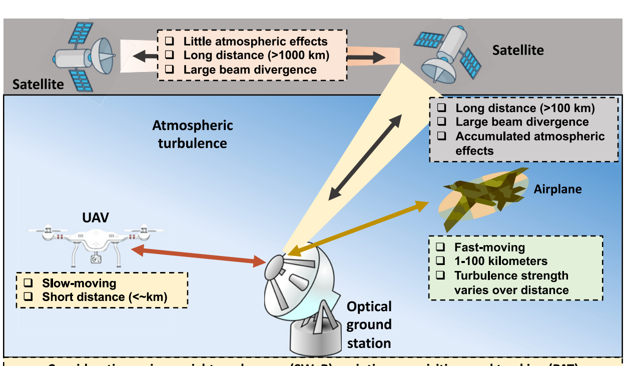

Figure 5: Orbital-angular-momentum (OAM)–multiplexed free-space optical airborne and satellite communications.

orthogonal beams, but a system designer could also use the other beam modal index in order to possibly achieve a larger two-dimensional set of data channels. This two-dimensional approach was shown experimentally for LG and HG beams [6, 34]. It is important to note that a significant challenge is the sufficient capture of the beam at the receiver aperture to ensure accurate phase recovery and orthogonality along both indices [34].

5 Photonic integration and component ecosystem

Back in the 1980s, many WDM optical communications experiments were performed on large optical tables using expensive devices that were often either not meant for communications or one-off, custom-built components. The development of cost-effective, integrated devices was deemed important for WDM to be deployed widely.

The same could be said about OAM-multiplexed optical communications. Many systems experiments were performed on large optical tables using devices that were not originally meant for MDM optical communications. For the future of mode-multiplexing to thrive, R&D in integrated devices would seem to be of signaficants. Indeed, we have been keen advocates of photonic integrated circuits for OAM-based optical communications, as can be seen in these quotes from our prior papers:

(a) *Nature Photonics, Interview* 2012 [40]: "Schemes for the generation, multiplexing and demultiplexing of OAM beams using superior SLMs or integrated devices would help to improve the maximum number of available OAM beams."
(b) *Advances in Optics and Photonics* 2015 [7]: "As was the case for many previous advances in optical communications, the future of OAM deployment would greatly benefit from advances in the enabling devices and subsystems (e.g., transmitters, (de) multiplexers, and receivers). Particularly with regard to integration, this represents significant opportunity to reduce cost and size and to also increase performance."

System development would benefit from a full ecosystem of devices, including the above-mentioned components as well as: (i) amplifiers that uniformly provide gain to different modes, and (ii) waveguides that efficiently guide OAM modes with little modal coupling.

Key desirable features for these integrated devices include [26]: low insertion loss, high amplifier gain, uniform performance for different modes, high modal purity, low modal coupling and intermodal crosstalk, high efficiency for mode conversion, high dynamic range, small size, large wavelength range, and accommodation of high numbers of modes. Other functions that could be advantageous include: (i) fast tunability and reconfigurability covering a range of OAM modes, and (ii) integration of an OAM communication system-on-a-chip that incorporates a full transceiver.

Finally, experiments commonly use SLMs to tailor the beam structure, but commercially available SLMs are generally bulky, expensive, and slow. Our favorite wishlist device would be the creation of a "super" SLM that has low cost, small footprint, large dynamic range in amplitude and phase, wide spectral range, high modal purity, fast tunability (the faster the better, to even encode data bits), and high resolution [41, 42].

6 Novel beams

The excitement in this field originated by the ability to utilize orthogonal structured optical beams. However, there is much work in the fields of optics and photonics on several types of novel variations of optical beams (e.g., Airy and Bessel types), with more being explored at an exciting pace.

Over the next several years, it would not be surprising if novel beams are used to minimize certain system degrading effects. There have been initial results for some of these concepts, but a partial "wish list" for novel beams could be beams:

(a) that are more resilient to modal coupling caused by turbulence and turbidity;
(b) that have limited divergence in free space;
(c) that are resilient to partial obstruction, such that their phase structure can "self-heal" (e.g., Bessel-type beams);
(d) whose phase structure can readily be recovered even if the transmitter and receiver are misaligned.

7 Quantum communications

Another important advantage of OAM orthogonality is that one can use OAM mode order as a data encoding scheme [43–46]. For example in the case of a quantum communication system, an individual photon can carry one of the many different OAM values; this is similar to digital data taking on one of many different amplitude values. A binary data symbol (i.e., one data bit) has two values of "0" and "1", whereas an *M*-ary symbol may have many more possible values ranging from "0" to "*M*–1". The number of data bits per unit time would be $\log_2 M$. If each photon can be encoded with a specific OAM value from *M* possibilities, the photon efficiency in bits/photon can be increased. This has the potential to be quite useful for quantum communication systems which are typically photon "starved" and of which qubits commonly can be encoded on one of only two orthogonal polarization states [46] (see Figure 7).

A larger alphabet for each qubit is, in general, highly desirable for enhancing system performance. However, there is much research needed to overcome the challenges in fielding an OAM-encoded quantum communication system, such as: (i) mitigating coupling among orthogonal states, and (ii) developing transmitters that can be tuned rapidly to encode each photon on one of many modes.

8 Different frequency ranges

Separate from using optical beams, free-space communication links can take advantage of mode multiplexing in many other carrier-wave-frequency ranges to increase system capacity. For example, OAM can be manifest in many types of electromagnetic and mechanical waves (see Figure 8), and interesting reports have explored the use of OAM in millimeter, acoustic, and THz waves [47–55].

From a system designer's perspective, there tends to be a trade-off in different frequency ranges:

(i) *Divergence*: Lower frequencies have much higher beam divergence, exacerbating the problem of collecting enough of the beam to recover the data channels.

(ii) *Interaction with Matter*: Lower frequencies tend to have much lower interaction with matter, such that radio waves are less affected by atmospheric-turbulence-induced modal coupling than optical waves.

There are exciting developments in the millimeter-wave application space, for which industrial labs are increasingly engaging in R&D in order to significantly increase the potential capacity of fronthaul and backhaul links [47, 52–55]. Advances in this area include the use of RF antenna arrays that are fabricated on printed-circuit boards [54]. For example, a multiantenna element ring can emit a millimeter-wave OAM beam by selectively exciting different antenna elements with a differential phase delay [55]. Moreover, multiple concentric rings can be fabricated, thereby emitting a larger number of multiplexed OAM beams [52, 53].

9 Optical fiber transmission

MDM can be achieved in both free-space and fiber, with much of the transmitter and receiver technology being similar. However, the channel medium is different, which gives rise to the following distinctions:

(a) There is no beam divergence in light-guiding fiber.

(b) Fiber has various kinds of inhomogeneities, and coupling can occur among modes within a specific mode group or between mode groups, thereby creating deleterious interchannel crosstalk [36, 56–59]; typically, intramodal group crosstalk is higher than intermodal group crosstalk.

The excitement around using MDM for capacity increase originally occurred primarily in the fiber transmission world, especially in research laboratories [35, 36, 60, 61]. There was much important work using LP modes as the modal set in fiber. However, since there was significant modal crosstalk when propagating through conventional-central-core few-mode fiber, MIMO-like DSP was used with impressive results to mitigate crosstalk [35, 60].

OAM has also been used as the modal basis set for fiber transmission, both for central-core and ring-core few-mode fibers [4, 36, 37, 62]. Importantly, the modal coupling itself can be reduced in the optical domain by utilizing specialty fiber that makes the propagation constants of different modes quite different, thus reducing intermodal coupling.

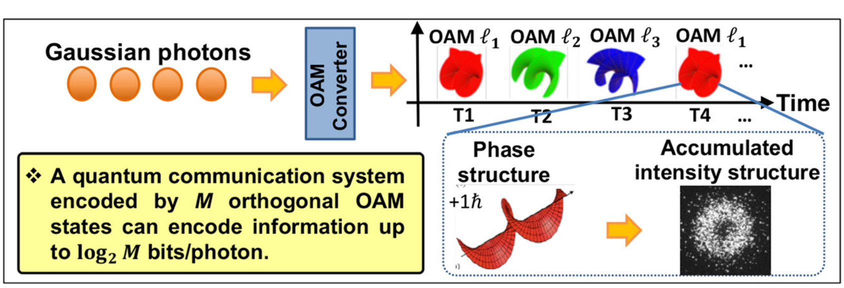

Figure 7: Concept of orbital-angular-momentum (OAM)–based quantum data encoding. Within each symbol period, a Gaussian photon is converted to one of the *M* OAM states, resulting in information encoding of up to $\log_2 M$ bit/photon. The accumulated intensity structure image is recorded using a single-photon sensitivity, low-noise–intensified charge-coupled device camera [46].

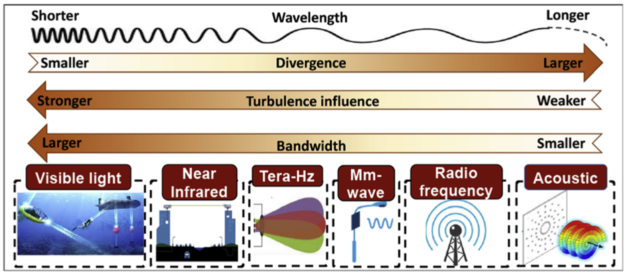

Figure 8: Orbital angular momentum (OAM) applications in different frequencies for communications.

Such fibers include ring-core and elliptical-core fibers [4, 36, 62], and 10's of modes with low crosstalk have been demonstrated. These specialty fibers have produced exciting results, but they are structurally different than conventional fiber and thus require a little more resolve in order for them to be widely adopted.

10 Summary

Will OAM be widely deployed in communication systems? Not clear. However, our opinion is that the R&D community is producing excellent advances that, with all likelihood, will be valuable in some important aspects that use structured light.

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