The working group in the breakout session on FSO short-range technologies addressed generic properties of domains where FSO is useful over short-range, identified a number of potential applications, and summarized the pertaining research issues. This section describes these three topics.

Generic Short-Range FSO Properties.

Short-range FSO is favored in applications where one or more of the following properties hold:

1) requires very high communications capacity AND goes where a physical link cannot (vs. RF, e.g. for emergency services, last-mile, drone/blimp),

OR

2) requires device high-density AND low-power consumption (vs. bluetooth or wifi),

OR

3) requires very low-latency AND high-bandwidth (vs. Satcom, i.e., arguing for short-range FSO),

OR

4) requires security; both robustness against interception as well as jamming (e.g., indoor application),

OR

5) requires ease of maintenance, economic considerations (e.g., vs. costly cable deployment).

Short-Range FSO Applications.

The working group identified a number of possible applications that could be improved by the introduction of FSO and VLC technologies. A brief description is provided for six cluster-areas that were identified by the working group.

Indoor Communications and GPS-free Localization.

FSO and VLC have the potential to achieve efficient indoor wireless communications, either diffuse or directed, either IR or visible, supporting high-speed, large numbers of users, and ubiquitous access. Achieving a robust and reliable network solution represents a challenge, i.e., we know how to do point-to-point very well, but wireless optical networks are still a problem due to occurrence of long burst of errors. We need to develop better switching, better protocols to handle the types of deep outages that can be experienced. There is also to consider convergence with already existing (competing) technologies: e.g., how do they coexist, augment, enhance, replace, RF and microwave systems? This is an issue for both indoor and outdoor networks. There needs to be a technical adoption approach for each application. The problem with the RF spectrum (the lower frequency nice part of it) is its limited bandwidth, but it also has great attributes: it is highly permeating, robust, easy to capture, etc. So the long term ideal is to rely primarily on optics (99%) for what optics can do well – lower mobility, high density areas, high throughput – and use RF only for backup, to add robustness to the system, and to handle a few expensive or hard-to-accommodate applications: transitional places, ultra-low densities, etc.

For indoor GPS-free localization, the existing techniques rely on triangulation from Wi-Fi access points. These solutions provide limited accuracy, compared to what can be achieved using FSO. Research challenges for achieving FSO based localization systems include how to integrate angle-of-arrival (AoA) detection from FSO/VLC links with received signal strength (RSS) detection, what are the practical and theoretical complexities involved in such hybrid localization designs, can it be done in-band within the FSO/VLC channels without having to worry about dedicated localization equipment, e.g., LIDARs. The advantages of achieving FSO-based localization include better accuracy and independence from licensed RF bands, e.g., offloading of traffic from RF bands to unlicensed optical bands.

Backhaul and Metro Networks.

Another application for FSO is outdoor short-range (100-1000 m) links, forming a highly connected and adaptive network to support 5G backhaul and beyond. These reasonably stationary-node networks can be used for wireless backhaul, last mile, private enterprise networking, bridging communities, etc. Current technologies include RF and fiber optics. Achieving a robust and reliable network solution represents a challenge, primarily due to adverse weather conditions. The entire protocol stack needs to be rethought in order to handle the types of deep outages that can be experienced. Research challenges include how to overcome the reliability challenges due to adverse weather conditions, how to best design mesh networks in an urban area – e.g., where to place FSO nodes and how many transceivers, if hybrid technologies are used, how to manage the hybrid network, etc. If successfully deployed in backhaul and metro networks, FSO technologies can yield larger aggregate bandwidth than RF solutions, and potentially lower deployment cost when compared to that based on fiber optics.

Disaster Recovery.

FSO offers a valid replacement for backhaul optical fiber in disaster situations (fiber cut) or in denied areas (fiber can't be laid, e.g. battle zone, between islands, mountainous/jungle terrain). As emergency service – FSO solutions can relatively quickly restore bandwidth capacity immediately during/after an outage, e.g., earthquake, hurricane, other natural or civil disaster, especially in the last mile within that area or for a backbone traversing that area. Note that this application is also a variant of early capacity deployment for military uses. Technologies that are suitable for this application include FSO, E band, and satellite. The need for both low power (so terminals can operate without infrastructure), high bandwidth, and low-latency make E-band and satellite technologies insufficient. Unfortunately, current FSO solutions are too expensive and difficult to rapidly deploy at the moment. Low SWaP and cost, easily deployable terminals with high bandwidth would be highly desirable. Phased arrays (to remove expensive gimbals) would be useful in this arena. Problems that must be address include automatic network configuration, robust distributed mesh routing, endpoint physical stabilization (especially when on a mobile platform, possibly including extensible poles and drones/blimps), eye safety (especially when signals may mesh around buildings). It is also important to identify solutions that compensate for link errors and fades, e.g., using redundancy, while maintaining low cost of deployment.

Last Mile Networking

Today's last mile networking leverages cabling and deployment of fiber lines. These solutions are costly, hard to deploy (right-of-way), and take considerable time to deploy. Service provides miss significant revenues when they cannot reach out to new customers in a timely fashion. FSO technologies can circumvent the inconvenience of deploying cables. Establishing robust and reliable FSO mesh networks remains the main challenge here. This involves link reliability against atmospheric dynamics (e.g., fog, rain, snow, bird). Wind can cause FSO antennas to vibrate/sway impacting signal allignment. Viable solutions may require the design of modulation techniques that are robust to such conditions. For example, a minor breakage on the FSO link may significantly disrupt a residential customer's experience. How can we best setup FSO backup paths? In addition, topology control and fast re-route mechanism will be needed. Installation costs of these FSO antennas in the last mile is expected to be another challenge. For example, how can we power FSO antennas without requiring power lines (e.g., solar power)? How can we accurately maintain alignment of FSO signals over time? If successfully deployed, FSO technologies will accelerate and enable high-speed connectivity deployment to residential and business areas that present obstacles to fiber deployment.

Inter-Rack and Chip-to-Chip Interconnects.

FSO may also find applications in inter-rack communication in data center. Today's solutions are based on optical fibers, kilometers of them! Most of the data centers are still using multi-mode fibers that cannot accommodate WDM, or PSK due to dispersion. To increase bandwidth, these current fibers need to be replaced with single-mode fibers. This is a significant capital investment that is not guaranteed to be future proof. Switching to FSO would ensure that the next generation of optical coding will be compatible with the infrastructure. Considering that a data center is a controlled environment, FSO can easily be implemented without running into the difficulties that are present in open areas such a line-of-sight, atmospheric constrain (cloud, rain, dust), eye safety. However, the challenge in deploying FSO technologies in data center is mostly engineering and cost. The most important metric for the client is $/bit, including CAPEX and OPEX. In OPEX, the power consumption is a huge factor and every watt spared in the electronics counts twice considering that it is not thermally dissipated and does not require cooling. FSO can become an attractive alternative to fiber if it can be implemented along optical switching, which is by far more power-lean when compared to electronic switching. Fiber injection after switching is a lossy process with at best 3dB loss - this energy consumption can be reduced if not entirely avoided by using FSO. Every time there is a transformation to or from electronics (storage and computation) to optics (communication), there is a substantial loss of energy. FSO technologies should be part of the ongoing effort to bring optics closer to the chip for a more energy-efficient data center (and supercomputing) architecture. In addition, FSO implementation for inter-rack communication makes the infrastructure future proof to upcoming optical coding and wavelength bands. The leading datacom band is the c-band at 1550nm because of the favorable transparency and dispersion in optical fiber. However, there are advantages going to shorter wavelengths such as visible from a pure data transfer point of view.

Chip-to-chip communication inside a computer is today ensured by copper lines on the PCB board, and have not changed since the invention of the printed circuit in the mid 20^{th} century. Even though the transistor and logic gate have been subjected to dramatic reduction in size and energy consumption (Moore's law), the same is not true for the inter-chip communication. In today's computer, most of the energy dissipated by the CPU is used to communicate. This is particularly true for supercomputers where the computation is scattered over several CPUs, and the results need to be shared for the task to complete. Entire classes of problems are defined as communication intensive rather than computational intensive due to the large amount of information that needs to be exchanged/shared between the processors. Without a substantial increase in inter-chip communication bandwidth density, and a similar reduction in the per-bit energy exchanged, our society cannot continue on its exponential trend of use of information. There are several areas of research that need to be covered for chip-to-chip FSO interconnect to become viable. For example, high-efficiency laser diodes and detectors, capable of achieving sub-femtojoule per bit; diffraction limited micro and nano optical elements, e.g., free form micro lenses, pattern generation holograms; integrated photonics compatible with silicon process: e.g., amplifier, modulators, wavelength multiplexer/demultiplexer, high frequency phase shifters; and low loss coupling: e.g., grating coupler, interconnect, optoelectronic packaging. The physics of FSO for in chip-to-chip communication addresses both the limitation in bandwidth and energy consumption, and has the potential to achieve orders of magnitude improvements over current solutions. It can be demonstrated by using the diffraction limited size of optical beams, the surface of the chip, and the chip clock rate, that a 20 Tb/mm^2 bandwidth density can be obtained. By improving the chip-to-chip communication, large problems can be solve much faster leveraging distributed architecture, first by increasing the number of CPUs involved in the processing task, and second by reducing the downtime imposed by the communication delay. The advantage of reduced energy consumption provided by FSO in inter-chip communication can also be beneficial for personal computers and portable devices, which will have improved battery lifetime. One can also image that an external port can be created using the same technology for inter-devices short range communication (laptop, smart-phone, cameras, harddrive) with extremely high data transfer rates.

Connectivity under Mobility.

FSO can also provide unique capabilities to applications in which mobility is key. Examples include vehicular technologies, communications between UAV/drones, robots in advanced manufacturing production floors.

In vehicular communications, DSRC or other proprietary solutions exist. They all depend on licensed RF bands. Adoption of FSO technologies here would provide independence from licensed RF bands and offloading of traffic from RF bands to unlicensed optical bands. Fast acquisition of an FSO/VLC link in a mobile setting remains the major unsolved issue. Discovery, pointing and acquisition of the optical wireless link will need to be very fast, e.g., in the other of milliseconds. Further, the transmitters and receivers will need to be inexpensive and seamlessly integrated to vehicles and transportation infrastructure. Line-of-site availability is another challenge that may limit applicability. Low cost FSO devices would enable massive deployment to offer multiple point of communications to overcome this limitation.

Communication in balloon networks or UAV networks is another application of interest. Google and Facebook are already experimenting with these solutions for offering Internet access to remote areas, where there are no alternatives. FSO is a potential candidate for providing connectivity and networking between UAVs and balloons. FSO has the bandwidth for providing access to large communities over other possible solutions. This is an emerging area that must be explored, though point-to-point FSO connectivity between balloons has been demonstrated by Google. Sustained FSO connectivity under mobility is a challenge. This requires improved PAT and multi-connectedness in order to maintain network connectivity in the face of uncertainty. Note that the uncertainty is due to movements of balloons/UAVs rather than weather at such high altitudes. Enabling Internet access to large swaths of populations in remote areas offer a significant premium. The research done in this area may also be helpful to other applications as well, such as disaster response.

Another potential application is communications that enables real-time control of advanced manufacturing robots. RF signals are today used to control and communicate with indoor robots and drones used for advanced manufacturing. However, they suffer from the following limitations:

1. RF signals interfere with drills and devices used for advanced manufacturing,
2. RF signals provide low positioning and tracking accuracy,
3. If many robots and drones are going to be controlled, contention could increase the delay,
4. RF signals are easily jammed.

Research challenges span from determining how to jointly perform communications and positioning, to determining which VLC positioning technique to utilize (AOA, RSSI, fingerprinting). Also relevant are techniques for achieving interference-free FSO by utilizing multi-element FSO. If successfully applied, FSO communications would help automate and improve advanced manufacturing processes, allowing more accurate control of robots movements and synchronization.

Short-Range FSO Additional Research Challenges.

One thing the working group struggled with was the difference between what we can do now versus in say 10 years. A fairly good consensus was reached for the need for basic research still. The following list captures some of the potential additional research challenges that were discussed during the breakout session:

a) automatic multipath routing (to deal with link fades/disruption and errors),

b) multipath error recovery (similarly to deal with link fades/disruption and errors),

c) rapid channel (re)configuration (fast PAT, fast signal lock, fast re-provisioning, etc.),

d) multicast/broadcast support (even at low bandwidth, possibly with diffuse or split-beam methods – this feature is needed to efficiently support IPv6 and other protocols),

e) design for low latency (pipelined where possible, using horizontal encoding across data streams rather than by buffering a single stream, etc.),

f) design for robustness (e.g., to address attacks on PAT, signal lock, channel management protocols),

g) design for security (e.g., low-latency encryption, low-latency authentication - considering message-splitting approaches that trade BW overhead to reduce latency impact),

h) integration of different channel types, including coherent, directed light, diffuse light, and RF,

i) development of 4 micron sources and detectors. Atmospheric effects and background noise will both be much less at this wavelength, so many applications (including automobile FSO/Lidar hybrids in fog) will be enabled.