Requirements and Challenges for Tactical Free-Space Lasercomm

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Abstract—**Mobile free-space Laser communications is the next frontier for net-centric connectivity, as bandwidth, spectrum and security issues drive its adoption as an adjunct to RF communications. However, key technology challenges must be addressed and mission requirements understood for it to emerge as a meaningful capability for dynamic tactical communications environments. We present a brief overview of the current military communication infrastructure and future needs, before highlighting terrestrial Lasercomm technology status and trends, and lessons learned from several experiments and field tests. Optical link service parameters and metrics are assessed in the context of available architecture and techniques, while the effectiveness of various technologies to mitigate atmospheric turbulence, poor weather and pointing/tracking inaccuracies is analyzed for improved reliability. Finally, the ramifications of cost and SWaP (size, weight and power), critical to tactical Lasercomm deployment, are considered in narrowing down these technology options.**

Index Terms— **FSO, tactical communications, free-space optics, MRR, scintillation, Laser communications, optical networking, QoS, FEC**

I. Introduction

FREE space Laser communications (Lasercomm in short), also referred to as free space optical (FSO) communications, has been studied for a long time [1][2], but only recently enjoying a resurgence as a serious communications modality, both in the commercial as well as the military sector. The fiber-optic revolution of the late 90's, in particular the birth of the EDFA (erbium doped fiber amplifier), heralded in high optical transmit powers required to overcome realistic link losses for IM-DD (intensity modulated - direct detection) systems in a cost-effective manner. Add to that the benefits of higher eye safety thresholds at mid-IR (infra-red) and the ready availability of high performance passive optics/detectors FSO links in the tens of Mbps could be realized over tens of kilometers (kms) in clear weather. Over short distances (few kms), links could be closed even in dense fog and bad weather. These were primarily 'fixed' terminal transport systems that set up high bandwidth connectivity under fiber-less infrastructure conditions, such as in the 'last mile', between down-town high rises. Now the focus is shifting to on-the-move and mobile systems which stand to benefit from this technology as improved beam pointing and tracking can yield robust line-of-sight data links. But challenges remain, especially in the tactical military domain, where robustness is a key consideration.

In this paper we discuss state-of-art Lasercomm technology, the atmospheric issues, the mobility challenges as well as what the future holds for technology readiness over the next five years. Comparing this against capability requirements that are derived from military mission and operations, we identify technology shortfalls that need immediate and near-term attention. Looked another way, we attempt to answer what are the mission scenarios and concepts of operations (CONOPS) where Lasercomm is most likely to be used and has a high probability of success in the tactical military environment .

II. Tactical Theatre and Mission Requirements

It is a well-known fact that modern warfare is evolving to net-centricity, where information flow between the enterprise and tactical side need to be robust and seamless, providing high bandwidth at the right quality-of-service (QoS) level to mobile platforms as well as disadvantaged users (ground combatants and dispersed sensors). Military and commercial SATCOM in the UHF, SHF and EHF bands, in addition to the line-of-sight (LOS) radios such as CDL, TSSR (GRC-39), HCLOS, DWTS/MRC-142 have hitherto served as high bit rate data pipes for ISR (intelligence, surveillance and reconnaissance), while non-LOS (NLOS) and beyond-LOS (BLOS) low data rate netted radios such as Link-16, HF-IP, SINCGARS and EPLRS have been used for C2 (command and control) and combat information sharing.

Multiple military missions, such as time sensitive targeting (TST), closed air support (CAS), anti-submarine warfare (ASW), expeditionary warfare operations, have one common thread – that is requiring ubiquitous connectivity, so commanders, both at the strategic as well as the tactical level can take quick and correct decisions closing the loop between

Manuscript received June 16, 2008. This work was supported in part by the U.S. Office of Naval Research.

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978-1-4244-2677-5/08/$25.00 ©2008 IEEE

sensors and the shooters. The combat and mission effectiveness, often denoted as a kill chain timeline, is reliant on good communications under stressed conditions – such as (i) requiring low latency, (ii) jammed electromagnetic spectrum, (iii) denied access to or unavailable SATCOM assets, and (iv) desire to remain covert, among others. Traditional RF communications modes, while sufficient or excelling on many fronts may prove vulnerable at one time or another, depending on real-time threats (unintentional cosite to active jamming) or performance shortfalls (low bit rate, large size/weight/power footprints). This presents a unique opportunity for Lasercomm to serve as an adjunct to RF communications, mutually reinforcing their respective strengths.

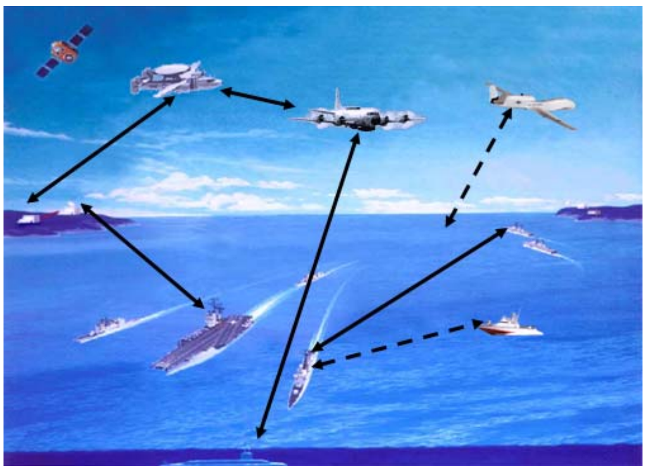

Fig. 1: Terrestrial tactical Lasercomm data links between airborne, surface and land nodes. Solid lines denote 'direct' bidirectional links, whereas dotted lines represent 'retro-reflector' links.

Fig. 1 shows example Lasercomm applications in the tactical battlefield, between land, surface (water) and airborne platforms. Example link distances up to 200 kms are not uncommon. ISR bandwidth will reach hundreds of Mbps. Platform mobility (for airborne) can easily exceed several hundreds of kms per hour. It is clear these metrics are difficult to achieve under adverse cloud, weather and atmospheric conditions, but an adaptive approach with bit rate tradeoff for distance under inclement weather may be acceptable. Also, certain applications, like pier-side (anchored ship to shore) communications over distance of few kms will be able to handle the severest of fog and haze, even at high data rates. Hence missions and operations may dictate where and how Lasercomm is applicable even under bad weather conditions.

Two modes of Lasercomm, the 'direct mode' and the 'retro-reflector mode', are of interest. The direct mode, between two symmetrical Lasecomm transceiver (transmitter TX and receiver RX) terminals as embodied in conventional FSO links offer very high bandwidth, in part, because of their large antenna gain. This antenna gain comes at the cost of requiring very accurate pointing and tracking. A typical FSO link uses beams with divergences of 1 milliradian or less. Generally a large gimbal, fast steering mirrors and a position sensing detector, such as a quad cell, are needed to maintain a link with such narrow beams. The size, weight and power requirements of such systems mean that small platforms such as small unmanned airborne systems (UAS) and unattended sensors may not be able to use conventional FSO. For many of these systems the two ends of the link are asymmetric in size. That is, in a link between, for example, a UAS and a ground station the ground station may have the capability of using a much larger terminal than the UAS. For these asymmetric links the retro-reflector mode may be a good choice. Example missions where retro-reflectors are highly advantageous include maritime interdiction operations (MIO) for exfiltration of biometric data from a boarded vessel to the host ship, and littoral mine warfare (LMW) operations involving transfer of ISR data from sensors to unmanned surface vehicles (USV).

III. PROPAGATION AND SYSTEM AVAILABILITY

We want to underscore the complementary nature of both RF and Lasercomm for tactical communications. Whereas RF can be LOS, NLOS or even BLOS, Lasercomm is necessarily LOS. Hence it is only prudent to compare the features and performance of Lasercomm to equivalent LOS RF, such as CDL or other directional apertures at Ku and Ka bands. In two important categories of cost and SWaP (size, weight and power), Lasercomm is predicted to yield significant reductions, at least by a factor of two or more, at equivalent bit rate and QoS metrics. This is because optical amplification is inherently more (wall-plug) efficient than RF amplification, given the high peak/average ratios typically encountered in RF waveforms. Further, fiber based optics have been miniaturized to a degree unprecedented in the RF world, partly owing to the wavelength dependence of the aperture, but more importantly due to rapid commercialization in planar light guide chip fabrication and integration.

Depending on the terrain (urban, canyon, foliage), environment (littoral, airborne, desert), and the weather (clear, foggy, rainy), the RF and optical propagation exhibit different degrees of dynamic fluctuations. This impacts link availability and robustness for each of these systems, but not necessarily to the same degree or extent, nor with predictable correlation. For example, ongoing testing and examination of channel sounding data for various dual-mode links (Ku and optical) suggest there may be a degree of complementarity in each of the system's performance given a combination of temperature and relative humidity conditions; i.e., one system works well when the other does not, given different atmospheric ducting conditions. From a scattering perspective it's also well known how mid-IR Lasercomm works well in light to moderate rain (improving with increased rain drop size), but not in fog, somewhat opposite to the RF performance one expects in the Ka band.

We should point out all Lasercomm propagation issues are not systematically studied and understood, even though empirical correlation with bit-error statistics and general link-availability results are available. For example the US Naval

Research Labs (NRL) has conducted a multi-year research effort to quantify the propagation of optical beams through maritime atmosphere and assess global maritime availability using satellite data from NASA's Global Precipitation 1 Degree Daily (1DD) database [3]. The test facility uses a 10 mile maritime path across the Chesapeake Bay, and has approximately 9 months of 24/7 atmospheric data collection which included measurement of angle-of-arrival fluctuations, power transmission, packet error rates (PER) of data transmitted at 100 Mbps and 1 Gbps, statistics of scintillation, and weather conditions [4].

The histogram in Figure 2 shows the distribution of the turbulence parameter C_n^2 (also called the atmospheric structure constant) observed during 2007. Generally speaking, the strength and variability of turbulence strength in the maritime environment is much less than observed over land. Approximately 99% of all measured C_n^2 values lie between $3x10^{-14}$ $m^{-2/3}$ and $1x10^{-15}m^{-2/3}$. These turbulence levels combined with the long clear LOS available over water make the maritime environment more suitable for operational Lasercomm systems than on land, as indicated by availability studies.

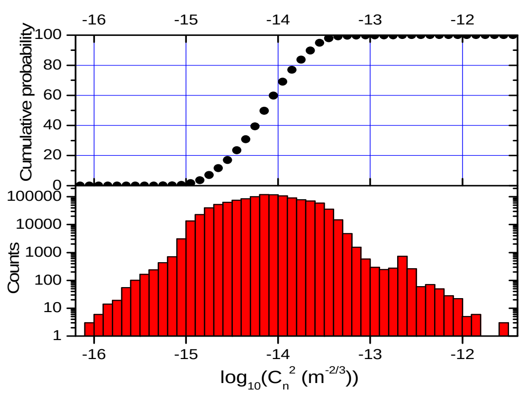

Fig. 2: Histogram and cumulative PDF for all C_n^2 data collected during 2007.

The NRL PER data shows the ability to close a link with a PER <1% approximately 90% of the time, with the 10% downtime due to atmospheric attenuation from weather. The 10% downtime was correlated with the precipitation data for the location of the test bed the 1DD database to arrive at a threshold precipitation value for outages in the link. The 1DD precipitation data to lasercomm availability correlation was then used to back correlate all precipitation data to determine availability across the rest of the globe (see Fig. 3). Note the parts of the graph that are over land are not valid data points since the correlation found is only applicable to the maritime environment. Also note that this is a rough approximation owing to the coarse temporal resolution (daily) of the 1DD data base and should be used only as a general guideline for lasercomm availability throughout the global maritime environment

In this paper we are dealing with long-range communication links, where the spot size at the Rx plane is at least several times larger than the Rx aperture. The intensity distribution according to the Rytov theory follows lognormal behaviour only in *weak* to *intermediate* turbulence. Experimental verifications show that lognormal behaviour of the received

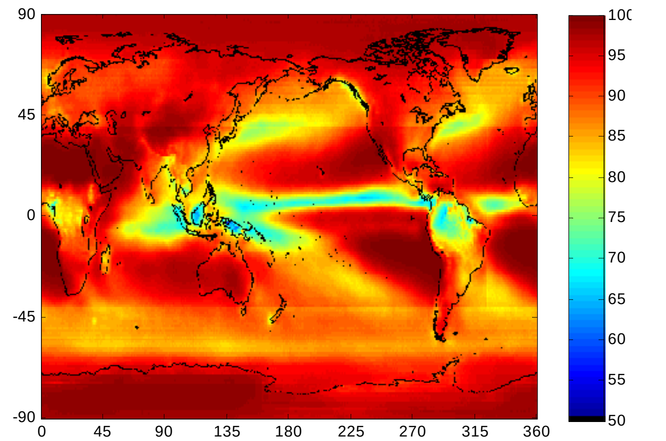

Fig. 3: Scaled availability estimate using NASA's One-Degree Daily Global Precipitation Database. Only data shown over water is meaningful

power P_{Rx} also applies to a good approximation in all turbulence cases *weak*, *intermediate*, *strong*, *saturation* in particular when some amount of aperture averaging take place [5]. The lognormal distribution is characterised by the variance of the received power, also called power scintillation index (PSI), which has been empirically obtained from various measurements shown in Table 1. Note PSI can also be calculated if values of relevant parameters, such as C_n^2, aperture diameter, wavelength, divergence angle, pointing/tracking error, etc., are known.

Scenario	PSI	λ *[nm]*	distance [km]	Rx-Ap [mm]	f_{3dB} [Hz]
land mobile link moving vehicle with 20 km/h, calm day	0.06	808	1.5	75	N.A.
long range stationary link (good weather conditions)	0.25	808	61	70	~10
Short range stationary link (all weather conditions)	0.05-0.15	1550	0.5	25	2 - 200
maritime mobile link	0.02-0.57	1550	18	130	20 - 80
LEO down link (clear sky)	0.01-0.95	848	2700 - 600	400	100 - 300

Table 1: Empirical values for the power scintillation index (PSI) from measurements

The temporal behavior of the received power can be modeled with good approximation to real life situations by filtering the log-normal distributed power values with a low-pass filter, whose 3dB cut-off frequencies values are given in Table 1. The cut-off frequency is mainly defined by the transverse motion of the air relative to the communication path. According to the frozen turbulence theory there is no difference if the air is moving through the communication path (e.g. wind) or the communication path is moving through the air (e.g. movement of the communication partners). For example the LEO downlink measurements have been taken during quite stable atmospheric conditions at night. For fixed links these conditions would have caused a low cut-off frequency, but the high velocity of the LEO satellite across the sky and therefore the fast movement of the communication path through the air causes relatively fast changes of received power. On the other hand, in the short range stationary link there were some measurements during which the air between the two fixed partners was in a very stable condition and the cut-off frequency was very low. But there are also measurements, where the weather conditions (wind, sunlit rooftops) caused strong air flows between the two stations and the cut-off frequency was measured in the same range as for the LEO downlink.

IV. MITIGATING ATMOSPHERIC SCINTILLATION AND TURBULENCE

Laser beam breakup and wavefront distortion through index-of-refraction turbulence (IRT), as well as slow temporary non perfect transceiver alignment are factors that cause slow fading of the optical received power. Depending on the fade level and receiver implementation these effects can cause a total link-outage of the communication channel for several decades of milliseconds. Several mitigating strategies include (i) wavefront distortion corrections, (ii) aperture averaging, (iii) spatial or path diversity (iv) time diversity including forward error correction (FEC) and automatic repeat request (ARQ), (v) network route diversity. We expect a combination of one or several of these techniques to be used to keep quality of service (QoS) acceptable. Furthermore, service level agreements (SLA) demand special requirements from the transport layer. Proactive and reactive protocols like FEC and ARQ can help close the gap between physical channel constraints (e.g., long power fades) and SLA (e.g. low latency). Analogous to ITU recommendations [6], for ‘conversational class’ low-bandwidth (< 2 Mbps) full-duplex applications (such as VoIP and video conferencing), a latency of 150 ms (400 ms max.) with 1% PER is a target QoS, whereas for high bandwidth (> 50 Mbps) ‘file downstream class’, such as streaming video, a very low loss rate (<< 1%) is an objective although the latency can be somewhat relaxed (< 1 sec.). These end-to-end service level performance requirements then drive the choice of techniques for turbulence mitigation.

The first method of turbulence mitigation is using adaptive optics, which must compensate for beam steering, focus control and higher-order wavefront distortion corrections [7]. These systems consist of a deformable mirror, tip-tilt mirror and a wavefront sensor with sufficiently fast feedback to the deformable mirror to adjust for atmospheric dynamics. Commercially available terminals featuring high bandwidth (>1 kHz) closed-loop correction of approximately 30 Zernike aberrations including tip-tilt and focus are now available. An added benefit of adaptive optics is the ability to focus the (highly distorted wavefront) laser beam on to a single mode fiber (SMF) with typical mode field diameter as small as 10 microns. The use of SMF coupling at the receive side is particularly attractive for exploitation of commercially mature technologies such as Dense Wavelength Division Mux (DWDM) for higher bit rates, optical pre-amplification for improved sensitivity (> -45 dBm @ 10 Gb/s), and optical automatic gain control (OAGC). (Note transmit side is never encumbered using SMF optics, for power amplification, etc.). Even then, for longer links (> 100 km), and while under a saturated turbulence regime, very large power fades in the order of 40-50 dB can occur which the adaptive optics is unable to compensate. An optical automatic gain control (OAGC) unit has been developed to maintain a constant average power to the WDM optical receivers, operating over a dynamic range of greater than 50 dB at sub-millisecond response. Figure 4 is a plot of the input and output signals of the OAGC [8]. The time interval is one second and the input optical signal is shown with power fluctuations from -47 to -5 dBm. The output optical signal is held at - 7 dBm with ~1 dB fluctuations.

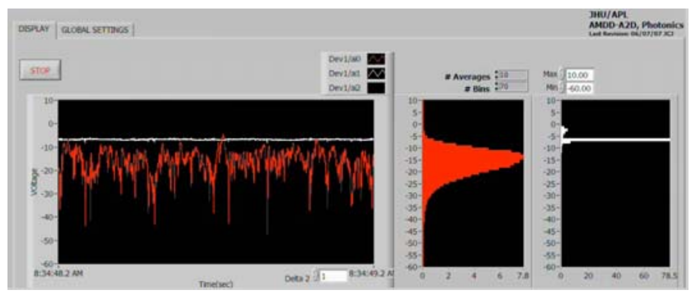

Fig. 4: Optical AGC data: Input optical signal (-47 dBm to -5 dBm) and output optical signal (held fixed at -7 dBm). The time axis covers one second and the plots on the right are histograms of the displayed data.

Increasing the effective receive aperture is a time tested method to mitigating turbulence. A novel switched InGaAs 2×2 Avalanche photo diode (APD) array technique to aperture averaging has been demonstrated as shown in Fig. 5 [9], without sacrificing sensitivity and bandwidth, and with low-noise large-area (100×100µm pixel) APDs with k-factors approximating 0.1, optical fill factor of 75% and bandwidths rated up to 2.5 Gbps. The decision circuit can either continuously scan each pixel in the array and choose the pixel with the most illumination, or sum multiple or all pixels depending on atmospheric conditions. The system, therefore, combines a high sensitivity, high speed receiver with the ability to actively track and compensate for beam wander within the focal plane. Furthermore, because the circuit continuously monitors and switches between pixels with the most illumination, the severity of atmospheric turbulence in a given setting can be measured by how often the circuit switches between pixels. If, for example, the circuit is switching frequently between multiple pixels, then turbulence is fairly high and multiple pixels should be summed to improve signal-to-noise. On the -other hand, if the circuit stays firmly on one pixel, then the atmosphere if reasonably calm and summing is not required.

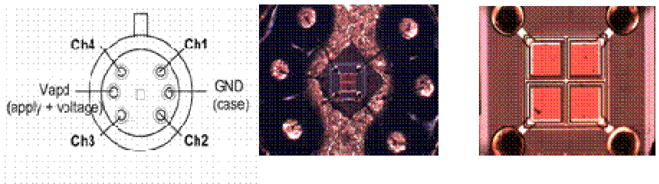

Fig. 5: TO-18 header layout 2×2 APD array with images taken at 2X and 10X magnifications

The third method of turbulence mitigation is making use of spatial transmit and/or receive diversity [10], to create at least two paths between the transmitter and receiver. For good diversity the separation between the transmitter/receiver should be typically 5 to 20 cm, depending on the scenario. Assuming these diverse paths are uncorrelated, then each path experiences independent fading, improving the overall system performance since the probability of all paths simultaneously experiencing a deep fade is quite small. If a large spatial separation is needed, such a system will be complicated to implement because every source and sink must be aligned. We believe spatial diversity technique is not well suited to tactical applications where equipment size and footprint are important issues.

The fourth method of turbulence control is the most cost-effective since implemented as error control in the higher protocol layers. Standard bit level FEC can be used to mitigate fading, but is not very effective due to constraint length issues [11]. Nevertheless, the bit level time-delay-diversity (TDD) approach [12]-[13] seems to be promising. Here bits are retransmitted after a delay longer than the channel coherence time, but the disadvantage is that available channel bandwidth is essentially halved – which may not be a serious issue for optical systems since they have inherently a greater throughput. However, this approach clearly shows that link latency can not be reduced to values shorter than fade durations.

The 'conversational class' traffic requires low latency but can tolerate some packet losses. A well configured (link-layer) ARQ point-to-point bridging protocol can manage to quickly retransmit lost data after an outage event [14]-[15]. An ARQ based solution has the drawback of additional complexity compared to TDD, because additional retransmission strategy and memory organization is needed. On the other hand ARQ uses the available bandwidth more efficient as it only retransmits the lost data. (TDD has the advantage that it can also be implemented for unidirectional links.) In bidirectional links, ARQ can also be used for securing the data transmission within the conversational class. As previously mentioned the outage time of the optical link is a limiting factor for the QoS parameters of an optical link, which can only be dealt with improvements on the physical layer. During a link outage the channel is in a state where most data is lost. Therefore it is not possible to successfully retransmit lost data within this state even if the data loss is detected.

If ARQ should be used in optical networks for jitter and delay sensitive services, the ARQ protocol should be used to secure the end-to-end communication and not the communication between the hops. The reason for this is that the number of hops per connection within the network is not fixed and might vary for every connection. If the ARQ protocol is implemented between each pair of hops it is not possible to calculate the overall delay for the end-to-end connection. This is because the overall delay depends on the number of retransmissions between the hops and the number of hops is not fixed. If one needs to control the maximum delay and jitter, hence the QoS of the connection, the communication should be secured by an end-to-end ARQ. In this case, the maximum number of retransmissions on the connection between the partners is controllable for each connection. The place where such an ARQ protocol should be implemented is between the link layer and the network layer to keep the system transparent to existing applications and protocol on higher layers.

The 'file downstream class' traffic requires high throughput and lowest error probability, but can tolerate higher latency. Physical layer coding can not reach the needed error probability, since deep fades are causing longer outage duration than physical layer codes can effectively deal with. Large code-symbol sizes (symbol size can be equal to link-layer packet size: *packet layer coding*) can help to overcome this problem. Such a code is for example the patent free Low Density Generator Matrix (LDGM) Staircase code. Other codes are *Lt*, *Raptor*, and *Torondo*. Packet-layer coding performance investigations and code dimensioning were discussed in [11] and [16]. In [17] and [18] it has been practically proven that packet-layer coding is suitable to overcome long-duration fades as observed over long range optical wireless channels. Fig. 6 shows an example of the

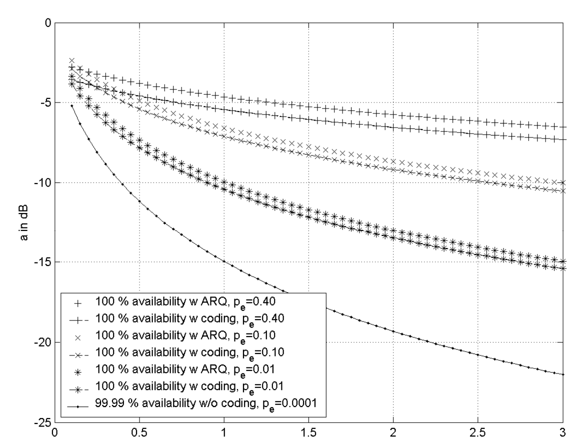

Fig. 6: Necessary margin in dB for almost 100% availability with packet layer Irregular Repeat-Accumulate codes and ARQ compared with uncoded transmission, as a function of PSI, and for different packet erasure p_e. [19]

necessary fade margin without error protection and for comparison with FEC and ARQ able to overcome certain packet loss probabilities. Fading is characterized by the power scintillation index. It can be clearly observed that with error protection the margin necessary to overcome fading can be significantly reduced. Further ARQ is always more effective than FEC. This is because FEC is working with constant overhead while ARQ is only retransmitting lost data.

The fifth and the most robust means of overcoming outage from turbulence or for that matter any bad weather or node failures is using network route diversity. But this comes at the price of increased network infrastructure, plus robust and efficient mobile ad-hoc routing protocols. Further, network coding can improve the error rate above and beyond what's possible in a single-hop system.

V. Minimizing Pointing and Tracking Inaccuracies

For pointing, acquisition and tracking (PAT), usually a two stages approach is followed [20]. The first stage is a coarse pointing assembly (CPA) which is used to discover a beacon signal from the partner terminal. The tracking sensor of the CPA has a relatively large field of view (FOV) in the range of a few degrees. Because of its large FOV the CPA is not accurate enough to properly align the receiver optics with the incoming signal. For a more accurate alignment of the receiver optics a fine pointing assembly (FPA) is implemented.

The FPA has a relatively small FOV and therefore a high angular resolution. The FOV of the FPA has to match the inaccuracies contained in the alignment made by the CPA. To reduce terminals cost, commercial of the shelf (COTS) cameras can be used as tracking sensors for the CPA as well as for the FPA, with the advantage that the actual tracking signal is generated by the image processing software and not by the hardware itself. The software algorithms can easily be adjusted to several tracking scenarios and can implement routines for filtering out disturbing sources like background light and reflections. Because of the robustness of the image processing algorithm it is possible to implement a larger FOV for the tracking sensor. With a larger FOV faster reacquisition is possible in cases where the tracking source has been lost e.g., due to blockings of the line of sight. Additionally the system is more robust against inaccuracies of the underlying tracking hardware like delays within the motor controllers, mechanical misalignment, vibrations. A disadvantage from the use of cameras is the limitation in achievable tracking rate. Most cameras can only deliver full resolution images at a maximum of 100 Hz or less.

If a higher tracking rate is required quadrant detectors offer a cost efficient solution, but they are sensitive to disturbances caused by reflections and the background light which can not be removed completely by signal processing or optical filters in front of the sensor. For mitigation of these disturbing effects, the FOV of the quadrant detector should be as small as possible and the tracking source has to be modulated in order to distinguish the beacon signal from other light sources. These system adjustments lead to additional system complexity and higher terminal costs. An additional advantage of quadrant detectors over cameras is that quadrant detectors do not need a designated processing unit, because they directly produce an electric tracking signal. Therefore they allow for the design of smaller terminals. In the terminal used in [21], a relatively large FOV quad cell was used for acquisition and tracking of both outer (gimbal) and inner (FSM) loop. Scanning of FSMs of both the transmit and receive paths further increases the field of regard for acquisition and works even with relatively large initial pointing inaccuracies (~1 degree). FPA can be used for bigger FOV and help especially with faster acquisition over larger FOV, but is neither always required nor necessary, since it is possible to change other system parameters to conform to the quality of the pointing accuracy by the CPA. This approach has been used, for example in [11].

Another important factor on tracking accuracies is the weight and size of the moveable mass of the PAT system. The mass of the parts that have to be moved for tracking determine the type of motors that have to be used for moving these parts. In general the more powerful these motors have to be, the more inaccurate the PAT with these motors becomes. For this reason an alternate implementation of moving the optics around, while keeping the electronics fixed was proposed [20].

The challenges for accurate pointing, acquisition and tracking between tactical mobile platforms with unique vibration dynamics, velocity/acceleration profile including those caused by rough sea states or uneven terrain, including possibly aero-optics effects cannot be underestimated. Terminal mounting with unobstructed view (full hemisphere coverage) is critical. Past experiments focusing on ship-to-ship communications [21], or between aerial platforms to ground [20], or satellite to ground [22] have shown encouraging results on the persistence of these LOS connections. Relatively simple systems have been built to close links over long distances in the maritime environment. These systems range from static systems which simply optimize pointing of a transmitter every few minutes to a large FOV receiver, to two gimbal mounted transceivers with fast steering mirrors able to compensate for ship roll, vibrations, and atmospheric tip/tilt of the propagated beam. Non-gimbal options for beam pointing and steering, such as employing Risley prisms [23] or even optical phase arrays (OPA) [24] are attractive if and when cost effective for tactical systems, however the gimbal terminals are predicted to be ready in the near future (3-5 years) at a cost point affordable for many aerial and naval platforms (US $50K-$100K per terminal).

VI. Overcoming Degradation from Clouds, Aerosols and Bad Weather

As is well known, Lasercomm, like any other technology, suffers from limitations governed by the laws of physics. In this case, given the wavelength of operation (commercial DWDM 1.5 um region for space and terrestrial applications) one has fundamental limitations due to scattering (such as Mie) from fog, clouds, dust, aerosols and other obscurants. Details of wavelength dependence of both short and long wavelength propagation in all weather has been investigated in [25]; it was concluded there were no intrinsic advantage in moving to a different wavelength for terrestrial applications.

A brute force approach to compensate the extreme scattering losses is increasing transmit power level at the expense of bit rate. This approach is the adaptive bit rate, but there are practical limits as fiber amplifiers are somewhat peak power limited. A double benefit of bandwidth reduction is a few decibels of receiver sensitivity may be picked up owing to the lower thermal noise, but this requires the receiver to dynamically adjust the feedback resistance. Also, heavy forward scattering as from clouds, can cause significant intersymbol interference, and signal may not be decoded with fidelity at the receive end. Path redundancy in air to ground terminals is a good solution for cloud avoidance, but not practical given infrastructure limitations. Coherent heterodyning has been analyzed as technologies worth pursuing to pick up receive sensitivity, as well to reduce the impact of background illumination, which may often be present for ground terminals looking in to the sky during daytime.[26] But these remain complex and expensive solutions, especially for smaller platforms and the benefit of heterodyning to direct detection for strong scattering channels is rather limited [1]. Recently more exotic techniques such as femto-second pulsing [27], and optical vortex modulation [28]-[29] are being pursued to address cloud and fog propagation, but these investigations are at their very early basic science research phase; they are unlikely to impact product development within the next several years.

Hence it appears there is no clear cut solution for performance impact, hence system availability, due to bad weather. There will be some incremental improvement from adaptive bit rates, pushing overall availability to the 90% range in longer links. For short links, such as pier-side communications, this may very well approach 99%. To achieve 99.9% availability, hybrid RF approaches as well as networking with path redundancy are the likely near-term solutions. Since many of the bigger platforms rely on a host of heterogeneous data links, we expect redundancy to overcome any bad weather intermittency for Lasercomm. For small platforms, low bit rate RF radios will need to pick up the slack for Lasercomm during mission critical operations. It is important to remember that the 90% (on average) of the time that Lasercomm is available, its high bit rate can enable almost instantaneous exchange, update and synchronizing of C2 and ISR information and situational understanding. In contrast, a slower RF link will be more vulnerable to intermittency (from jamming say) and high probability of intercept, while operating 24/7 in tactical environments.

VII. Modulating Retro-Reflector (MRR) Optical Links

As discussed earlier, 'retro-reflector mode' holds great promise for tactical communications. The 'direct mode' communications is the conventional FSO link. In a MRR link, a conventional, actively pointed, lasercomm terminal on one end interrogates an MRR on the other end of the link with a continuous wave laser beam, as shown in Fig. 7. This beam is passively retro-reflected back to the interrogator with a signal imposed upon it by the modulator, creating the so-called 'retro-reflector' mode of communications. MRR links have similarities and differences from conventional FSO links. As with conventional links, MRR links depend on laser power, beam divergence, pointing accuracy and receiver diameter, but for an MRR link these parameters are all determined by the interrogator. Unlike conventional FSO links, MRR links must transit the atmosphere twice, so atmospheric attenuation is higher and in addition they fall off as $1/R^4$ instead of $1/R^2$. The MRR parameters that affect the link are the MRR's optical antenna gain, its modulation efficiency, and its modulation bandwidth.

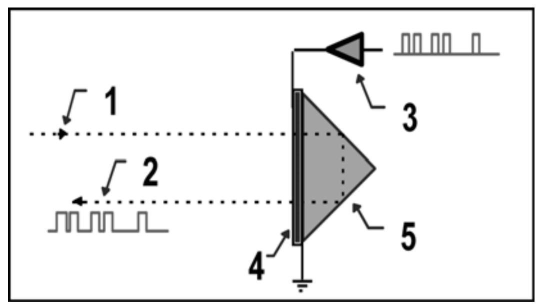

Fig. 7. Diagram of a modulating retroreflector. 1: The incoming beam, 2:The outgoing, modulated beam, 3: The data source, 4: The multiple quantum well modulator , 5: The corner cube retro-reflector

To overcome its large propagation losses the MRR must exhibit a high optical antenna gain (also called its optical cross-section). The MRR acts as a receiver, intercepting the light of the interrogator, and a transmitter, re-emitting the light as its retro-reflects it. Thus its optical antenna gain is the product of the classical formulas for receiver gain and transmitter gain and has a very strong dependence on retro-reflector aperture. In fact since both the antenna gain and the range dependence scale as fourth powers, doubling the aperture of an MRR doubles its range. It is also important to maintain near diffraction limited performance from the optic. - The optical modulator at the retro-reflector will have its own optical loss and contrast ratio, both of which affect the returned signal strength. These two parameters can be combined into one figure of merit, the modulation efficiency. Given an MRR's antenna gain and modulation efficiency, an MRR link can be expressed in terms similar to a conventional FSO link.

In general MRRs can be categorized in terms of their modulator technology and the type of retro-reflector that they use. MRR based on ferro-electric liquid crystals [30], MEMS devices [31]-[32] and multiple quantum well (MQW) electro-absorption modulators [33]-[36] have been demonstrated recently. In general liquid crystal and MEMS modulators are limited by their intrinsic switching speeds to data rates of kbps and hundreds of kbps respectively. MQW modulators are generally limited in data rate by their RC time. Hence, depending on aperture size and retro-reflector type, MQW modulators can have rates from about 1 Mbps to hundreds of Mbps.

MRRs have typically been corner cube prisms. The modulator can cover the face of the corner cube or be a reflector acting as one or more of the sides of the prism. For modulator technologies whose speed limitations are due to material switching rates corner cubes are probably the best retro-reflector choice. But for RC limited modulators corner cubes can impose limitations. This is because the modulator must be the same size as the retro-reflector aperture. In principle, an MQW modulator can have rates in the Gbps. However, a high bandwidth link requires more light. That can be achieved by using a larger retro-reflector, but in a corner cube system that will increase the capacitance of the modulator thus increasing its RC time and slowing its response. One way around this issue is to use a cat's eye retro-reflector and place the modulator in the focal plane [37]. For a cat's eye MRR the modulator can be very small, about the size of the focal spot. But if it is to work over a finite field of view an array of small modulators must fill the focal plane. This is because the location of the focal spot will change with angle of incidence. To maintain high speed and low power operation the cat's eye MRR can be coupled to an angle of arrival sensor (which can be the modulator itself) so that only the illuminated pixels need to be driven with the modulator signal.

For the past ten years NRL has worked on the development of MRR systems based on MQW modulators. Operating wavelengths have varied from 850 nm to 1550 nm and increasingly more sophisticated MQW structures have lowered the required drive voltage form 20V to 5V [34],[38]. We have investigated both corner cube and cat's eye MRRs. Corner cube devices have often been configured in arrays to broaden their field of view. Figure 8 below shows an array of corner cube MQW MRRs.

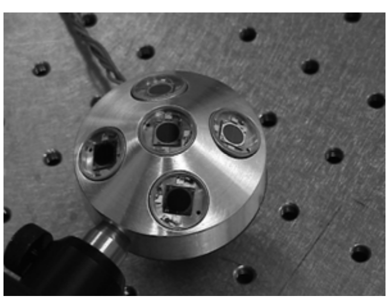

Fig. 8: An array of 6.3 mm corner cube MQW MRRs

We have also investigated a variety of cat's eye MRRs ranging from those based on simple commercial-off-the-shelf telecentric lenses [37], to sophisticated diffraction limited cat's eyes such as the one shown below in Fig. 9. Using these MRRs and both tracking and non-tracking interrogators we have demonstrated a variety of links. These include links to a small UAV [39], video links to boats at ranges up to 3 Km [40], cat's eye MRR links at rates up to 45 Mbps [37] and lower speed cat's eye links at ranges up to 16 Km.

MRRs fill a valuable niche for sensors and platforms that can benefit from FSO, including a low cost point (US $500-$1K). They offer the same advantages of low probability of intercept/detect anti-jam and freedom from frequency allocation as conventional FSO links. However they allow these advantages with far less platform impact. This advantage is offered at a sacrifice to the data rate or range, as limited by the $1/R^4$ range dependence, as well as the need for light to propagate through a, possibly, scattering path twice. However, within the bounds that these limitation set lie many important applications

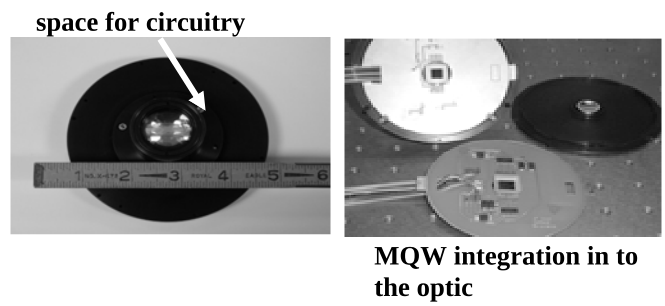

Fig. 9: A 1.6 cm diffraction limited cat's eye MRR

VIII. EXPERIMENTS, DEMONSTRATIONS AND LESSONS LEARNED

Numerous Lasercomm experiments and demonstrations in the last several years have proved beyond a shade of doubt their performance and potential capabilities for strategic and tactical communications [7], [20], [21], [41], [42]. The EU-FP6 project CAPANINA (Communications from Aerial Platforms providing high bandwidth communications for all) proved the feasibility of optical inter-HAP (high altitude platform) communication as backbone links for a HAP communication network. The German Aerospace Center (DLR) built a prototyped stratospheric optical terminal which was flown at 22 km altitude on a balloon. It provided a high rate 1.25 Gb/s high-quality (good BER and low latency) optical downlink down to a fixed ground station with a 40 cm receive aperture. With a single 100 mW transmit-power signal at 1550 nm a stable link was demonstrated which could cope also with thin clouds. For the uplink two beacons separated by 40 cm were used to support tracking [20].

The EU funded MINERVAA (Mid-Term Networking Technologies In-Flight and Rig Validation for Avionic Applications) project aims on the development of technologies for future aeronautical broadband networks. An optical link is foreseen as high data rate connection between aircrafts building up a network, thus enabling new applications for passengers such as Video on Demand or High-Speed Internet Connections. MINERVAA has started in 2007 and will complete with an aircraft to ground demonstration in 2009, proving the operability of required technologies. These include investigations in Pointing and

Tracking, Optical Terminal Design and packet-based Forward Error Correction, among other topics.

The satellite downlink from low earth orbit earth-observation satellites is a very promising future technology to overcome the downlink-bottleneck in earth-observation missions. To demonstrate the feasibility and robustness for this approach, DLR carried out the KIODO-experiment (Kirari Optical Downlink to Oberpfaffenhofen) together with the Japan Aerospace eXploration Agency. The Japanese test satellite Kirari carries an optical communications terminal which was pointed towards DLR's optical ground station during passes in June 2006. Under almost clear sky conditions uncoded bit error in the range of 1e-6 could be measured using conventional intensity-modulation with a rate of 50 Mb/s. It has been shown that transmission quality strongly depends on the satellite elevation and range because of changing link length and portion of atmospheric path in the link. It was pointed out that active control mechanism, e.g. transmit-power control, are necessary in order to avoid clipping of receivers.

Based on the experience gathered during the KIODO trials the Optical Communications Group from DLR is developing FSO test transmitter for space named OSIRIS. The terminal is tailored for use on compact satellites comparable to DLR's BIRD satellite and does not have any active pointing assembly. Therefore it can only be used on satellites that can operate in a target pointing mode, like earth observation satellites. The OSIRIS terminal is designed to deliver data rates 50 Mb/s up to 2.5 Gb/s.

In the MOND project in summer 2006 [43], DLR demonstrated the applicability of Lasercomm for military mobile scenarios. In this project, an uncompressed HDTV live stream was transmitted without using error protection form an arbitrary moving reconnaissance vehicle to a static network node with a data rate of 1.5 Gb/s and a link distance of about 2 km.

NRL, together with its dual mode optical interrogator (DMOI) terminal partner NovaSol, Inc., demonstrated during the Trident Warrior 06 exercise high data rate Lasercomm between operational large deck Naval platforms in transit from San Diego, California, to Honolulu, Hawaii [21]. The systems were installed as stand alone systems with no electrical connections to the ships except for power. One terminal was installed approximately 150 feet above the waterline on the USS Bonhomme Richard (LHD-6), and the other terminal was installed approximately 100 feet above the waterline on the USS Denver (LPD-9). The full duplex data transmitted between the two moving ships was typically uncompressed digital audio/video from handheld cameras at a data rate of 300 Mbps to up to 9 nautical miles.

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NRL is also fielding a FSO communication system for use in Maritime Interdiction Operations (MIO) during the Trident Warrior 08 Sea Trial exercise in June, 2008 [44]. The system utilizes a 3rd generation compact dual mode optical interrogator (compact - DMOI) developed by Novasol, Inc. to interrogate NRL developed MRRs. The 3rd generation DMOI allows eye safe operation at output power levels up to 1.5 Watts. The compact DMOI will be installed on the USS Comstock and the portable MRRs will be transported to various vessels of interest to close 2 Mbps links at ranges from 0.25 nautical miles (Nm) to beyond 1 Nm. The main goal of this experiment is to investigate the capabilities of a retro-reflector link to transmit data obtained during a MIO operation. The successful demonstration of this for MIO operations will enable diversified communication paths that will allow operation in situations where RF sources are inoperable due to multiple possible causes – RF interference, jamming, spectrum allocation issues, lack of host nation approval, etc.

In August 2007, a 147 km FSO communications link between Maui (Haleakala) and Hawaii (Mauna Loa) was demonstrated as part of a combined hybrid RF/FSO link demonstration, IRON-T^2 [8]. It was conducted with JHU-APL (optical modem, optical AGC), AOptix Inc. (FSO terminal with AO) and L3 Technologies (RF link and Iron T^2 router). The IRON-T^2 project was sponsored by AFRL (US Air Force Research Labs) to demonstrate a high-altitude air-to-air tactical link. The goal of this test was proof of concept demonstration of a long-distance FSO data link with lower-speed all-weather RF backup. Two WDM channels were used bi-directionally throughout the test - one supporting the hybrid link experiment and the other supporting a 10 Gbps channel. The optical link used two AOptix R3.1 Adaptive Optics (AO) compensated FSO terminals coupled to commercial 11" telescopes with a transmit power of a few hundred milliwatts at the output aperture.

Data was collected over a four week period. The performance of the link can be characterized by the power in the fiber (PIF) data. The power fluctuations due to atmospheric turbulence can vary dramatically even over one test cycle. During good conditions, the power fluctuations are on the order of 10 dB with absolute power from -10 dBm to -20 dBm. As the turbulence conditions worsen, the total power coupled into the fiber decreased and the variance increased. Typically, the PIF was between -50 dBm to - 25 dBm as conditions worsen. The variance increases until the turbulence conditions saturate. Once the link is saturated, the variance no longer increases, even while the absolute power may continue to decrease. Optical AGC/modem system (at 10 Gbps) has measured BER = 10^{-12} at -31 dBm (without any FEC) received power, with a dynamic range of 50 dB.

IX. Conclusion

We have discussed the prospect for high bandwidth Lasercomm, as an adjunct to RF, as a communications modality for tactical military applications. It is clear the advantages of Lasercomm over RF go beyond simple bandwidth expansion, to scenarios where anti-jam and low-intercept operation may be required, and/or where SATCOM access is denied, or when RF spectrum unavailable. A side benefit is also likely to be low size, weight, power and cost when compared to equivalent RF systems – making a compelling argument for this technology, especially in the use of retro-reflector mode for asymmetric data transfer. Existing technologies are successfully addressing performance enhancements in areas of turbulence mitigation and beam pointing/tracking, while new technologies and techniques may one day address fundamental issues with cloud penetration and bad weather. Nevertheless the state-of-art FSO technology is ready to deal with the Lasercomm development needs for the tactical battle space within the next five years.

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