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Laser communication with modulated retro reflectors - progress report

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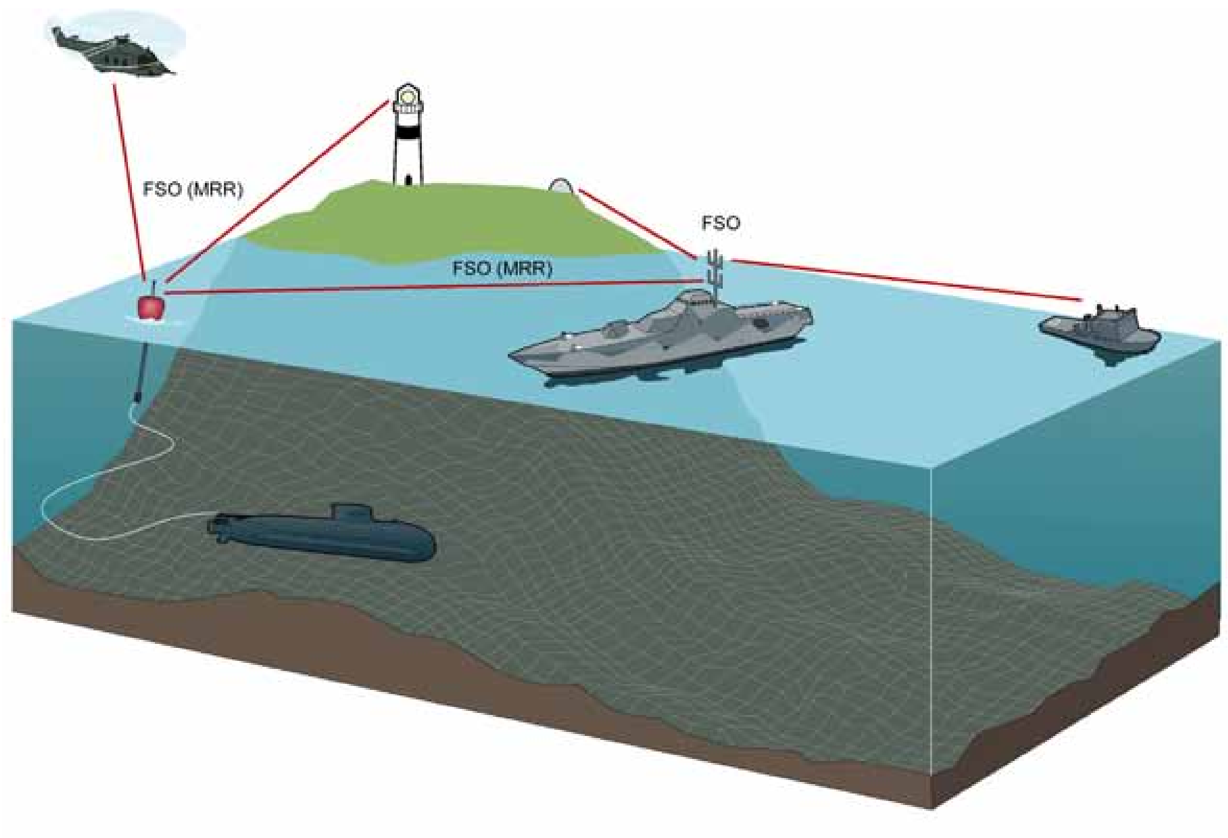

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Report title

Laser communication with modulated retro reflectors - progress report

Abstract

This report summarises this years's work in the FOI project ”Retrocommunication in tactical applications”. We have been leading a cooperative programme within the Western European Armament Group named ”Free space optical communications in tactical applications”, EUCLID CEPA TA No. 108.077. The goal of the study was to find follow-up projects of common interest within the field. Free-space (wireless) optical communication as a tactical method for future operations, e.g. within the framework of European battlegroups, was evaluated. Six European countries participated. A main conclusion was that transfer of data from a tactical UAV is a highly prioritised application for the majority of the participating nations. A demonstration of a free-space high data rate link, using modulated retro reflectors from a UAV with small load capacity was a suggested follow-on project. The experimental work of the past year focused on the development of a new laser unit with the simultaneous ability to transmit beams of different wavelengths with the aim of studying correlation properties. An application is to guide a weak quantum channel carrying laser beam of a quantum key distribution link with a stronger laser beam. The degree of correlation between two laser beams of different wavelength under the influence of a turbulent atmosphere was measured. The influence from turbulence on the received signal was studied. We also carried out a pilot study on coding and modulation techniques suitable for retrocommunication systems. Finally, in cooperation with Acreo AB, we have developed and assembled a modulated retro reflector in the so called cat's eye configuration, operating at 1550 nm with a modulation bandwidth of 10 MHz. The device was assembled at Acreo and the measurements were made at FOI.

Keywords

Free space optical communication, modulated retro reflector, laser, atmospheric propagation, multiple quantum well, modulator.

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Rapportens titel

Laserkommunikation med modulerbara retroreflektorer - statusrapport

Sammanfattning

Den här rapporten sammanfattar årets verksamhet inom FOI-projektet "Retrokommunikation i taktiska tillämpningar". Vi har lett ett samarbetsprogram inom "Western European Armament Group" benämnt "Free space optical communications in tactical applications", EUCLID CEPA TA No. 108.077. Förstudiens mål har varit att hitta gemensamma uppföljningsprojekt av intresse inom området. Syftet var att utvärdera fri optisk kommunikation som en metod i taktiska tillämpningar med relevans för framtida operationer t ex inom ramen för europiska stridsgrupper. Sex europeiska länder har deltagit. Slutsatser från studien är främst att kommunikation av data från en taktisk UAV är ett högprioriterat område för flertalet europeiska länder. Här finns en möjlighet att i ett gemensamt fortsättningsprojekt demonstrera en fri optisk länk med hög datatakt från en UAV som har liten lastkapacitet med utnyttjande av så kallade modulerbara retroreflektorer. Det gångna årets experimentella verksamhet centrerades kring en ny laserenhet med möjlighet till samtidig sändning av strålar med olika våglängd. Korrelationsgraden, under inverkan av turbulent atmosfär, mellan två laserstrålar vid olika våglängd uppmättes. Turbulensens inverkan på den mottagna signalen studerades. Vi har även genomfört en inledande studie om vilken kodnings- och modulationsteknik som är lämplig för retrokommunikationssystem. Slutligen har i vi i samverkan med Acreo AB tagit fram retromodulator av "Cat's Eye" typ som arbetar vid 1550 nm med en modulationsbandbredd på 10 MHz. Utveckling av retromodulator har skett vid Acreo och mätningar på FOI.

Nyckelord

Fri optisk kommunikation, modulerbar retroreflektor, laser, atmosfärspropagering, multipel kvantbrunn, optisk modulator.

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CONTENT

1 Introduction

This report summarizes the activities during 2006 within the project denoted ”Retrokommunikation i taktiska tillämpningar”, numbered E 3076. This is the second year of this project. The activities and results achieved during the first year was summarized in [1].

Free-space optical communication (FSO) i.e. laser communication through the atmosphere is an area under rapid progress due to the development of new photonic components. Data transfer rates well in excess of other potential alternatives are becoming viable and the technology is generally well suited to heterogeneous networks in the future battle space. Tactical links based on retro-communication, that is, laser communication with modulated retro reflectors (MRR) have many different applications. An MRR link has a steerable laser terminal in one end and a MRR terminal in the other. The risk of interception and the power consumption is low since no active transmission is required in the MRR terminal. Transmission of data from small platforms e.g. UAV and buoys have been considered. It is also a potential method for optical tags e.g. to distinguish the own troops from enemy troops in battlefield situations

The project have the following objectives:

- Study how laser/MRR based communication links can be used e.g. for the transfer of sensor data in tactical situations.
- Provide a foundation for the evaluation of the usefulness of MRR links in the future priority tasks of the Swedish armed forces.
- Study atmospheric effects with emphasis on turbulence and how these can be counteracted with new technology.
- Identify and evaluate critical components for MRR links.

The overall goal of the work is to demonstrate transmission of data at a high rate.

2 European (CEPA) collaboration program 2005–2006

The study “Free Space Optical Communication for Tactical Applications” was carried out within an information exchange program which was agreed upon in the EUCLID CEPA8 Technical Arrangement No 108.077. Belgium, Spain, Germany, Sweden, and the United Kingdom were the participating nations. Sweden was the lead nation of the program.

The study started in June 2005 and was planned to last for about one year. It covered five work packages:

- WP 1 Systems and Applications (from a user perspective) [2]
- WP 2 Technology survey (from the provider perspective) [3]
- WP 3 Atmospheric propagation and compensation methods [4]
- WP 4 Potential performance of selected links [5]
- WP 5 Project proposals for a follow-up program [6]

The purpose of the joint program was to evaluate FSO communication from a tactical point of view with reference to defined situations of relevance for future tasks that can be assigned for instance to common European battle groups. A general comparison of FSO with radio frequency links was made. Future tactical requirements were also discussed and analysed. Several applications having high priority in future tactical situations involving platforms such as unmanned aerial vehicles, helicopters, naval vessels and combat vehicles were identified. The technology is also suitable for other applications, for the individual soldier and in the future also for underwater applications.

In WP1 the tactical applications for FSO communication were discussed and analysed. The technology was briefly described and compared with existing conventional technologies. Especially the MRR technology may provide enhanced information superiority due to the high capacity available for rapid transfer of information. The MRR optical links also sustain covert high security transfer of data. Since volume, weight and power consumption are critical issues for several platforms and also for the individual soldier, MRR capability may provide an attractive way to extract and transfer information. In view of the studied tactical situations the extraction of sensor data based on MRR techniques for UAV to ground communication links was recommended with the highest priority.

The principle of FSO communication was described and its pro and contra discussed in WP2. The availability of a FSO communication channel depends on the transmission of the atmosphere and on the availability of line-of-sight (LOS). Atmospheric transmission is the most difficult hurdle for high availability in stationary ground-based FSO links. The LOS issue in stationary ground-based links can be minimized by using multiple beams in order to mitigate the effect of birds and other temporal blockages. In addition, careful selection of the site of the equipment can minimize effects like building sway or blockage that breaks the LOS. In non-stationary FSO links, stabilized and controlled LOS can be the hardest technical issue. For mobile applications, maintaining the LOS is much more difficult since the movement of the platform and the varying terrain can break the LOS and thus reduce overall availability. The critical components were discussed and technical gaps identified. A comprehensive survey of FSO commercial products and existing demonstrators was also presented.

In WP3 the impact of atmospheric effects on FSO communication links was described and solutions for atmospheric compensation techniques were discussed. For the most dominant disturbances of the signal beam like phase distortion, beam wander, beam spreading, and scintillation atmospheric compensation techniques were evaluated. Turbulent atmosphere may be modelled as a log-normal fading optical communication channel having a large coherent bandwidth, a long coherent time, and significant dispersion in space and spatial frequency. Simple phase-compensation systems may improve performance of optical communication links in most practical situations.

WP4 investigated scenarios where FSO communications techniques offer a clear benefit over existing RF techniques. The main drivers were the need for larger bandwidth, security and interoperability. The discussion of specific scenarios for high data rate reach-back, naval environment, and for reconnaissance with UAV showed major potential for network enabled capability. The investigations identified the most significant operation benefits for using FSO communication links for tactical UAV applications and a growing need for quantum cryptography. These communication bottlenecks will not be solved by currently proposed RF technology.

In WP5 demonstrators for FSO communication systems are proposed which are based on the findings of work packages WP1 to WP4:

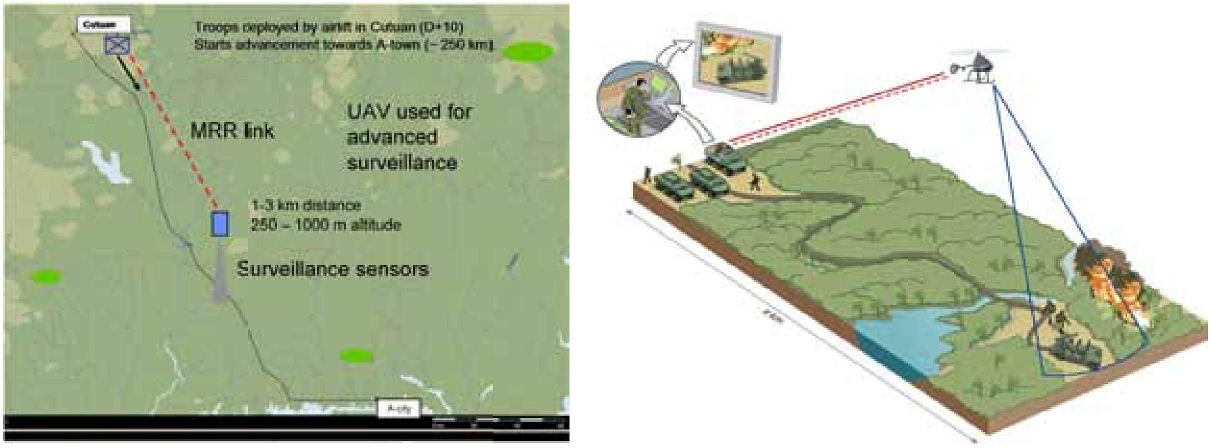

Figure 1 *FSO in a tactical UAV application.*

FSO-Communication Demonstrator (FSOCD) for UAV-Ground Application

There are large variations in the possible payload design for UAV depending on size and mission of the UAV. This will have a strong impact on volume, weight and power consumption for any built-in communication link. This large variation was taken into account by the group by splitting the proposal for UAV-Ground Application in two proposals: one for a small UAV (S-UAV) with a total payload of about 1 kg and one for a large UAV (L-UAV) with a total payload of about 30 kg. The weight for the FSO communication part should not exceed 10 % of the total UAV payload.

S-UAV-Ground Application

The main goal for this demonstrator is to show the possibility to reduce the volume, weight, and power consumption as much as possible and still offer a superior data rate with respect to RF technique having the same restrictions. The target for the data rate should be approximately 1 Mbps at operational S-UAV flight conditions. The target for the range performance should be 500 m with low bit-error-rate (BER) on the following atmospheric condition: Visibility ≥ 1 km, turbulence $C_n^2 \leq 10^{-13}$ m $^{-2/3}$. The group members indicate the highest interest for this proposal because there are already small tactical UAV in service which could immediately use such FSO communication links. The majority of the group voted for the highest priority for this demonstrator proposal.

L-UAV-Ground Application

The main goal of this demonstrator is to show maximum performance in range and/or data rate at operational L-UAV flight conditions. The target for range performance and data rate should be 2 km and approximately 10 Mbps respectively on the following atmospheric condition: Visibility ≥ 1 km, turbulence $C_n^2 \leq 10^{-13}$ m $^{-2/3}$.

FSOCD for Ship-to-Ship Application

The main goal of this demonstrator is to show maximum performance in range, covertness of the link, and/or data rate at operational ship movement conditions. The target for range performance and data rate should be 8 to 10 km and approximately 100 Mbps respectively with the following atmospheric condition: Visibility ≥ 10 km, turbulence $C_n^2 \leq 10^{-13}$ m$^{-2/3}$. Aspects of FSO communication backup solutions for RF communication links should be taken into consideration.

FSOCD for Underwater Applications

The discussion on other FSO communication applications identified a maritime scenario with underwater communication to have very high potential value. Upcoming underwater UAV with imaging systems, for instance based on the technique of gated viewing, will definitely need broadband communication links to the monitoring ship. The communication from airborne platforms to submerged submarines is another high priority topic. For both applications the FSO communication technique is the only solution because acoustic offers not sufficient bandwidth and RF has extremely short penetration depth into water. Underwater FSO communication still needs some fundamental research. Therefore the group proposed to initiate an EDA activity on this topic.

3 Quantum key distribution with modulated retro reflectors

During this year some preliminary investigations related to the potentially useful application of quantum key distribution to a modulated retro reflector optical link were made[7, 8]. Quantum key distribution would be an interesting service in various military scenarios to provide distribution of secure cryptographic keys. A tactical optical link combined with a quantum channel can potentially be of use for this purpose although there are some difficulties that need to be addressed.

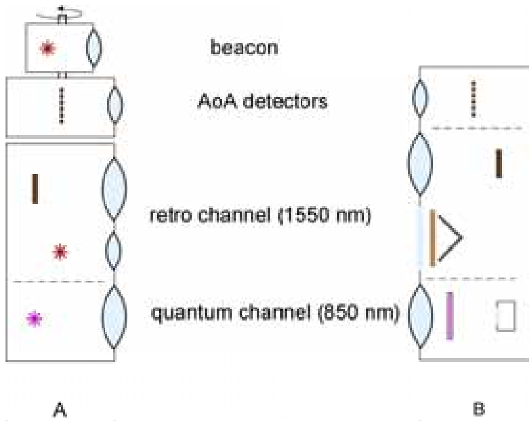

Figure 2 *Schematic description of the functional components in a tactical optical link with a quantum channel. In unit A, hosting all sources, a beacon (laser) is used for initial acquisition in cases when a link must be established without prior knowledge of the relative positions. Angle of arrival detectors (AoA) in both units delivers the direction to the opposite unit. The retro channel is used for classical communication at 1550 nm and the beam is additionally used for continuous fine tracking to sustain the link. The quantum channel is one-directional with the light beam going from A to B. The quantum transmission is steered using channel data from the 1550 nm link.*

The general idea is that the weak light beam of a quantum channel, at a wavelength of 850 nm, can be steered and controlled by a stronger 1550 nm signal in a retro communication channel. Figure 2 is schematically describing the components in the two terminals of a potential tactical optical link incorporating a quantum channel. In the end, the functional requirements depend on the platforms carrying the communication equipment and the tactics. One example is an aircraft, potentially an UAV, which is delivering quantum keys to battlefield or naval units. After distribution the securely delivered keys can be used in any available communication applications (not only the optical link). Terminal A hosts all light sources in this example. The contact is initiated when the beacon light is detected in terminal B. This terminal can then be opened to allow for retro-reflection of the beacon light after which the angle of arrival (AoA) detectors or some other means for coarse tracking (e.g. infrared camera systems) steer and align the two terminals. A required continuous regulation of the alignment can be anticipated in particular if any of the terminals are mounted on a vibrating vehicle. This fine tracking regulation will be a functional part of the retro channel which can turn on as soon as the two terminals are within the field of view of each other. The retro channel is then used both for the continuous link acquisition and for the classical communication which is required in addition to the quantum communication in a quantum key distribution (QKD) scheme. Many of the optical functions are possible to integrate in the same technical components, e.g. in order to minimize the number of optical apertures. The laser sources can use the same optics, a single laser can be used both for the beacon and communication function and multifunctional detectors can be used. In order for this to work it is of outmost importance that the classical channel is actually well correlated to the quantum channel. A potential problem was identified to be the turbulence and its impact on the two channels.

A dual-channel laser unit, with output beams at 850 and 1535 nm, was used to characterise turbulence effects along an atmospheric path close above ground. The laser beams were retro reflected from a corner cube and detected in the same laser unit. The 1535 nm beam was monitored with a position sensitive detector while the 850 nm beam (low intensity channel) was aligned with the 1535 nm beam and detected separately but along the same optical axis of the laser unit. Effects of beam wander, angular fluctuations and intensity scintillations were studied experimentally at different turbulence strengths and weather conditions.

The general idea of this work was to allow a weak 850 nm beam be guided into the same optical path as a stronger 1550 nm beam in a retro communication link. The potential application is to allow for QKD from mobile platforms. In addition to be an information channel the 1550 nm laser system is used for the link acquisition and is providing information about the instantaneous power and the angle of arrival. It was found, when the turbulence is ranging from weak to moderate, that the 850 nm beam is quite well correlated with the 1550 nm beam which was also expected from theory. However, the correlation strength is higher at 800 meter than at 128 and 400 meters which cannot be explained by theory. The normalized cross-covariance was around 0.6 at the shorter ranges and 0.8 at 800 meters.

A conclusion, based on the work, was that the 1550 nm optical power scintillations signal was well synchronized with the 850 nm signal. Hence, the 1550 channel can be used to control the transmission in the 850 nm channel e.g. to send signal burst when the transmission is at maximum. The angle of arrival fluctuations caused by weak to moderate turbulence were, as expected from theory, on the order of 20 μrad or less. It became apparent from this study that tip-tilt corrections on this order of resolution will be limited by the detector performance. At the same time it was found that the angle of arrival fluctuations caused by the atmosphere are typically quite small.

4 Cat’s eyes retro modulator at 1550 nm

Modulated retro reflectors are light-weight and require little power. Therefore they are often used in asymmetric free-space communication systems with limited capacity in terms of weight and power at one end of the link.

There are two main designs for the retro reflector: 1) the corner cube prism or 2) a focal plane reflector, commonly known as cat’s eye when designed to give a large field of view. The corner cube has the advantage of offering a deliberately large aperture, increasing the transmission throughput, and also has a large field-of-view (FOV). The cat’s eye on the other hand is based on lenses, which focus the laser beam onto a mirror. Thus it is harder to achieve a good optical performance with a large aperture (large lenses), and the FOV will be smaller.

However, the cat’s eye works well together with the best modulators available today (Figure 3). The modulators, having a semi-conductor structure, have a limited size and cannot cover the surface of a corner cube. On the other hand, they are large enough to hold the spot of the focused laser beam in the cat’s eye. Furthermore, the modulators are pixelated, and the laser spot will hit different pixels for different angles. In this way the modulator can be used to determine from which direction the laser beam is entering the cat’s eye and different signals can be modulated onto the beam from different pixels. Thus angular multiplexing is possible. For all, the pixelated structure of the modulator increases the modulator speed, as the RC-value is inversely proportional to the pixel size.

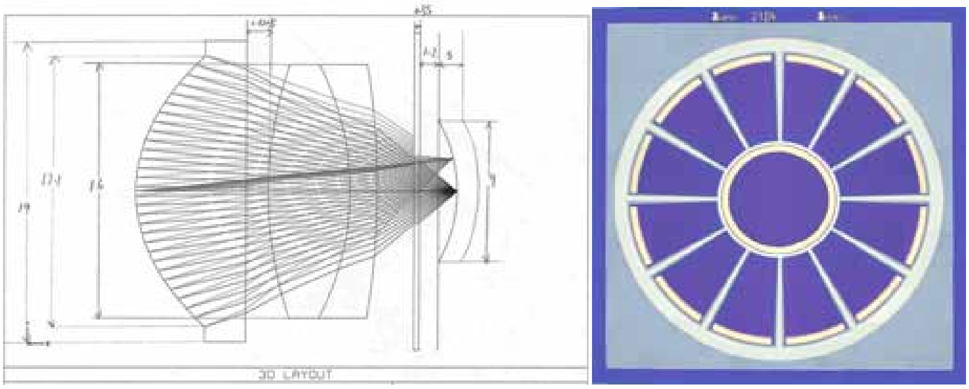

Figure 3 *The figure to the left shows an optical design of a cat’s eye MRR. The laser beam is entering from left and is focused by the two lenses. It traverses the modulator and hits a curved mirror. When properly focused, the beam will leave the MRR in the exact opposite direction. The right-hand figure depicts the modulator surface with a pixelated design.*

The design of the cat’s eye should exhibit a large aperture, a wide FOV and a well-focused beam. The system was optimized by help of the ray-tracing software ZEMAX, using the minimum wavefront errors and spot size criteria. The result, shown in Figure 3, contained an aspherical lens, an achromat lens, the modulator and a spherical concave mirror. The components contributed to a large FOV of 18 degrees with reduced aberrations – the design was in fact diffraction-limited. It had a 12 mm aperture and 13.3 mm effective focal length. We also developed an alternative design with a larger aperture of 17 mm for comparison. The cat’s eye was used in conjunction with an InP-based segmented modulator [9, 10] with an active diameter of 4.5 mm for wavelengths about 1550 nm. The cat’s eye and the modulator thus formed a MRR. Initial measurements with the MRR have been performed at distances up to

200 m in an indoor measurement facility. The MRR and one extra cat's eye without modulator (Figure 4) were placed on one end of a free-space optical link and interrogated by a laser transceiver.

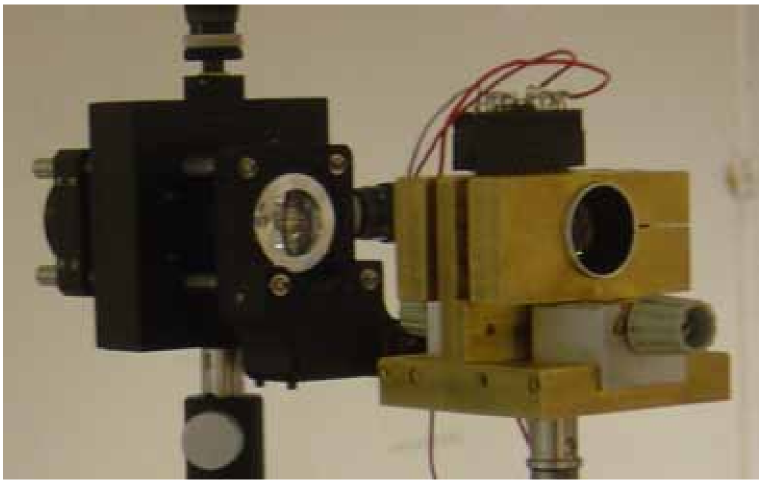

Figure 4 *Holder with cat's eye but without modulator to the left. MRR with cat's eye retro reflector and InP-modulator to the right.*

It could be concluded that the positioning of lenses and mirror had a large impact of the transmitted power. Especially the on-axis distance between mirror and lenses, determining the focus spot size, and the lateral distance of the mirror were of importance for transmitted power and the irradiance distribution of the beam. The MRR was tilted with respect to the laser beam as well, confirming a reasonable FOV. The performance at longer distances and higher modulation rates could not be tested at this initial measurement.

The InP-modulator is anticipated to have a modulation rate of 10 Mbps. Also, according to simulations in ZEMAX (Figure 5), it should be possible to increase the link distance considerably. To reach this performance, the electrical driving circuitry, the optical detector and the mechanical mount of the MRR might need to be improved.

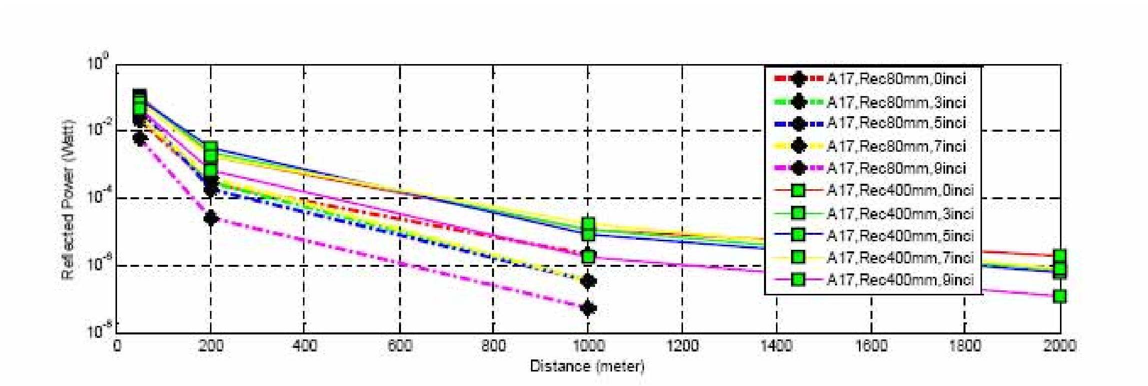

Figure 5 *Simulation of reflected power from a MRR with 17 mm aperture at different angles and two different apertures of the receiver.*

With further engineering, more sophisticated cat's eye systems can be developed to provide diffraction-limited performance over a wide FOV at large aperture. The development of the cat's eye at Acreo and the measurements at FOI is described in a report [11].

5 Coding and modulation

An MQW-based MRR has a variable reflectance and information can thus be transmitted to the receiver by modulating the intensity of the reflected signal. However, current experimental systems normally use binary modulation (e.g. on-off keying) and the data rate is then strictly limited by the modulation speed of the retro reflector. Instead, by employing a multiple-level modulation scheme the data rate can be increased substantially [12]. We investigated if the use of different signal processing techniques, commonly used in radio communication systems, can improve the robustness and data rates of MRR free-space optical communication links [13]. Techniques of interest are mainly error-correcting codes, link adaptation and high-level modulation schemes. An example of a possible design of a future adaptive MRR FSO communication system is shown in Figure 6.

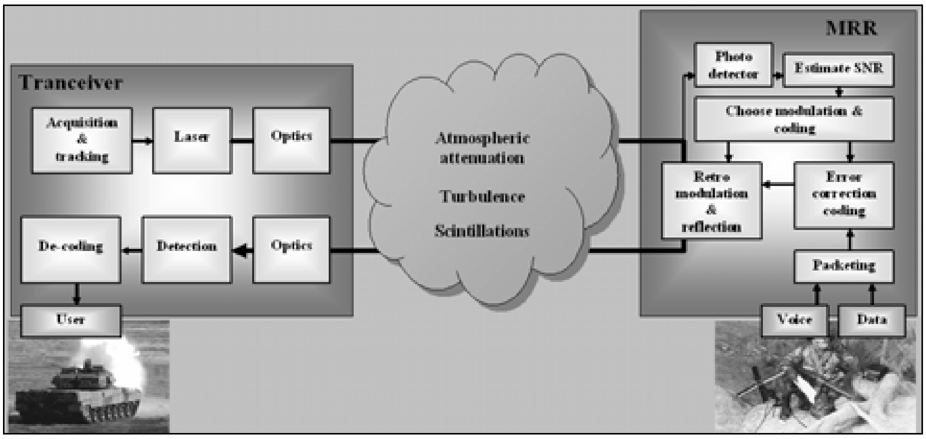

Figure 6 *Illustration of a possible adaptive modulated retro-reflective communication system.*

Through simulations we demonstrated the potential gains that can be achieved on measured real-world channels through the use of link adaptation and multiple-level modulation. In binary modulation the MRR varies its reflectance between two different states. Ideally, for a “zero” bit none of the light energy from the illuminating laser should be reflected back, while a “one” bit would mean that all of the laser intensity would be reflected. All retro-modulators have losses but the idea is to minimize the absorption in the MRR when a one is to be transmitted. When applying multiple-level modulation, more than two reflectance levels are used in the MRR unit. For instance, when applying a four-level modulation scheme (i.e. transmitting two bits per symbol) the reflectance when transmitting “00” could be about 20%, while the two bits “01” could be modulated by applying a reflectance of 40%. Similarly, the bit combinations “10” and “11” could be modulated by applying reflectances of 60 and 80%, respectively. Hence, with a four-level modulation scheme, we may then transmit two bits instead of one bit during the same time period. Thus, the data rates are no longer determined solely by the modulation speed of the MRR unit.

Now, when performing the detection (i.e. making the decision on which bits were actually transmitted), different decision algorithms may be applied. An intuitive approach is to calculate a set of thresholds on the received signal intensity mainly by continuously estimating the average, and possibly also the maximum and minimum, received signal intensities. Using a binary modulation scheme there is a single threshold and the bit decision is based upon if the signal intensity lies above or below the threshold. However, when using a multiple-level modulation scheme, several thresholds are used instead.

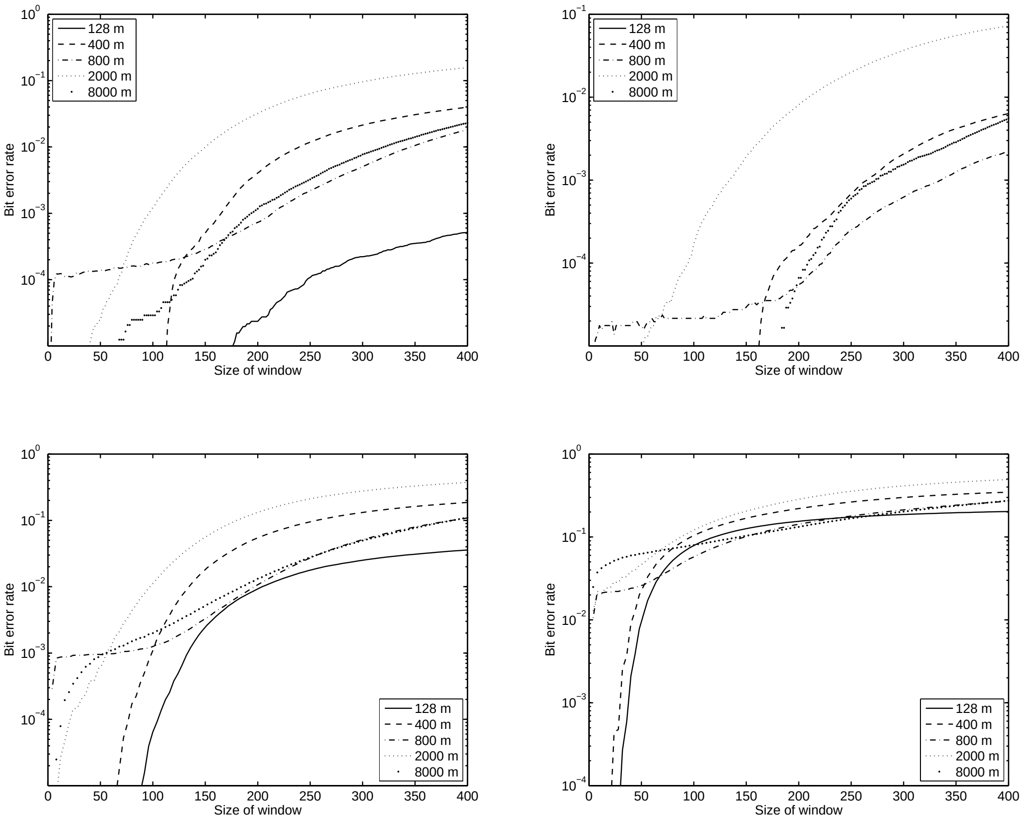

Figure 7 *Simulated bit error rates for different window sizes (used to estimate detection thresholds), for measured channels over different Tx-Rx distances. The used laser wavelength was 1535 nm. Binary modulation was used for the two upper plots, while four-level modulation schemes were used for the two lower plots. A modulator contrast ratio of 1:2 was used (100 % and 50 % for 1 and 0, respectively) for the upper left plot, while a modulator contrast ratio of 1:4 was used (100 % and 25 % for 1 and 0, respectively) for the upper right plot. A four-level modulation using levels 25 %, 50 %, 75 % and 100 % was used for the lower left plot, while the levels 40 %, 60 %, 80 % and 100 % were used for the lower right plot.*

Using four levels instead of two means that two bits are transmitted for each symbol. Thus, the data rate of the system is doubled. From Figure 7 it is clear that the bit error rate increases by applying multiple-levels. If a simple threshold detection system is to be used, it is pertinent to accurately estimate the threshold level with short window sizes due to the time-variability of the channel and the reduced decision intervals for the detection algorithm. The performance of the modulator is also significantly more important for a multiple-level modulation scheme; the bit error rate increased substantially when using a modulator with contrast ratio 1:2.5 instead of 1:4.

Hence, it may be desirable to adapt the number of modulation levels to the channel conditions. When the signal-to-noise ratio (SNR) is low a binary modulation should be used while multi-level modulation should be used in situations with high SNR. Ultimately, the system should adapt to the SNR with different predefined coding and modulation modes. In order to measure the SNR a photo detector can be used at the MRR. By sensing the signal intensity at the MRR it will in many situations be possible to accurately estimate the received signal strength also at the transceiver; thus, it is possible to perform adaptation of modulation and coding in the MRR. Also, it is possible to let the transceiver send accurate information to the MRR about the current signal levels. If the MRR has current and accurate channel state information the modulation level and code rate (which determines the percentage of redundant bits) can be chosen so that the highest possible capacity can be achieved while still keeping the bit error rate below a desired target value. Most modern radio systems employ adaptive modulation and coding, and it is a mature technique that should be useful also in future retro modulation systems. An adaptive system is expected to yield an increased capacity and robustness when the link is subjected to turbulence or a varying attenuation due to the environmental conditions.

6 Atmospheric propagation

Atmospheric turbulence may be an essential problem close to ground and usually degrades the performance of FSO communication systems. The deteriorating effects include beam broadening which reduces the optical power, beam wander, angle of arrival fluctuations and intensity fluctuations (scintillations). When the turbulence is strong, beam wander and scintillations may cause signal fading and an increase in the bit error rate. The turbulence will also affect the tracking performance in a non-stationary link, both by a reduced signal to noise in the directional measurement and by a reduced pointing accuracy. Quantifying the magnitudes of turbulence effects experimentally is important for validation of models and predicting performance. For tactical FSO communication links propagation paths which are horizontal, or weakly slanted, are of interest both over ground and sea. Experimental turbulence studies have been carried out with nearly horizontal paths investigating parameters such as amplitude characteristics, fading and tracking behaviour [14, 15]. Scintillation and fading probabilities in a double propagation path were studied. Analytical and statistical models provide an efficient tool for relatively fast calculations of the influence from turbulence effects on performance of FSO communication systems. In addition to analytical and statistical models numerical beam propagation methods have been employed. Scintillation and beam wander effects in a ground to satellite uplink have been modelled to study the robustness of the optical communication channel.

Turbulence measurements along various paths close above ground have been carried out. Two laser beams of different wavelengths were collinearly directed along the paths and retroreflected back to detectors. Synchronous acquisition allowed for a detailed comparison of the signal characteristics. Some basic aspects from a theoretical point of view were compared with the experimental results obtained in a series of measurements[8].

7 Final remarks

A workshop will be held in the beginning of 2007 at the European Defence Agency. We have argued together with the other involved nations that a demonstrator with communication of sensor data from a UAV is of common interest in Europe. We are currently in a position where we can participate, together with Acreo AB, and take the responsibility of the modulated retro reflector units in such a work. However, funding and a decision is required in order to be able to proceed.

A reduced budget for 2007 makes it necessary for us to focus our work even further. We plan to make measurements with the cat’s eye based modulator developed this year and test if multilevel coding is allowed for by the modulators.

8 References

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