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MIMO Transmission Capabilities to Increase Data Transmission Rates Between Disconnected Tactical Entities

Singh, Gurminder; Ateshian, Peter; Keeley, Psul; Stewart, Eric

Monterey, California: Naval Postgraduate School

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NPS NRP Executive Summary

MIMO Transmission Capabilities to Increase Data Transmission Rates Between Disconnected Tactical Entities

Report Date: 10/15/19 Project Number (IREF ID): NPS-19-N354-A

Naval Postgraduate School Graduate School of Operations and Information Science

NAVAL RESEARCH PROGRAM

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

MULTIPLE INPUT/MULTIPLE OUTPUT TRANSMISSION CAPABILITIES TO INCREASE DATA TRANSMISSION RATES BETWEEN DISCONNECTED TACTICAL ENTITIES

Executive Summary Type: Final Report
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Principal Investigator (PI): Dr. Gurminder Singh, Graduate School of Information Sciences (GSOIS), Computer Science Department
Additional Researcher(s): Peter Ateshian, GSOIS, Computer Science Department
Student Participation: Maj Paul Keeley, USMC, Information Warfare Systems Engineering/Applied Mathematics, Maj Eric Stewart, USMC, Information Warfare Systems Engineering/Systems Engineering

Prepared for:
Topic Sponsor Lead Organization: NIWC-PAC
Topic Sponsor Name: Dr. David Wayne, Engineer and Dr. Burton Neuner, III, Scientist, Advanced Photonic Technologies
Topic Sponsor Contact Information: david.t.wayne@navy.mil, 619-553-3064, and burton.neuner@navy.mil, 619-553-2885.

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EXECUTIVE SUMMARY

Project Summary

The strength of the highly networked Joint Force to apply lethality at the lowest level requires the ability to communicate data from the tactical edge. Threat actors throughout the world have developed sophisticated electronic warfare techniques, which can be used to jam or target friendly radio-frequency (RF) emissions; therefore, the Joint Force needs to develop options for tactical communications in a RF-denied environment. One option to augment existing communications systems is the use of free space optical (FSO) communications, which employ a high bandwidth, narrow beamwidth channel, characterized by a low probability of detection and interception. This could have significant military applications, ranging from communications between dispersed tactical units to datalink capacity between surface units and aerial relays. However, FSO communications in the atmosphere are characterized by additive white Gaussian noise and turbulent fading, which combine to significantly reduce the usable throughput of such a channel.

Our research affects the Naval Information Warfare community, and supports the pillar of Assured Command and Control. As such, it describes theoretical system requirements for overcoming these problems, while simultaneously increasing throughput, based on a multiple input/multiple output (MIMO) FSO channel. Several key systems architecture decisions are highlighted, and a full factorial design architecture of experiments is used to explore the breadth of the design space. Optimal candidate architectures are then identified through a tradeoff analysis between the bit error rate (BER), transmission rate, and power consumption. The principal coding-related research question was determining how a combination of forward error correction (FEC) encoding techniques might be applied to improve the reliability and efficiency of the MIMO FSO communications channel. This portion of the research tested thirteen coding and modulation schemes in software under different simulated levels of noise and turbulence, to determine which characteristics of the codes most critically affect performance. The results identified the probability of outage of such a MIMO channel as the most significant channel parameter. Additionally, we found that MIMO architectures employing more than eight sub-channels provide significantly increased protection against turbulent fades.

Keywords: *systems engineering, information sciences, free space optical, FSO, multiple input/multiple output, MIMO, systems architecture, low probability of detection, LPD, low probability of interception, LPI, forward error correction, FEC, low probability of exploitation, LPE*

Background

As a high bandwidth, narrow beamwidth channel, FSO communications can potentially achieve high data rates with a low probability of detection and intercept. Single input, single output (SISO) systems such as the Tactical Line-of-Sight Optical Network, are currently being pursued by the Department of Defense. However, SISO systems are susceptible to line of sight limitations, and high levels of atmospheric loss. MIMO optical systems, on the other hand, have the potential to overcome these limitations by providing spatial diversity and redundancy to the transmission.

This research explores ways to take advantage of this diversity and redundancy to efficiently and effectively encode transmissions. Possible use cases include: communications between dispersed tactical units such as reconnaissance elements, firing units or scout observers and short-term, high-rate datalink capacity between surface units and unmanned or manned aerial relays. Ranges could vary from less than 500 m (as in a dispersed artillery battery), to 10 or more kilometers (as when conducting expeditionary advanced base operations).

Andrews and Phillips (2005) describe the atmospheric FSO channel in depth, and its communication application challenges are also noted by Chan (2006), Kaushal and Kaddoum (2015) and Alouini, Yang and Gao (2014). Mitigation techniques include diversity, FEC, and multi-user scheduling, respectively. Application of two-dimensional codes to an array of FSO transmitters was recently experimented with at the Naval Postgraduate School (NPS) by Adrian Felder (2018), who used a dynamic sequence of Quick Response (QR) codes to pass data between an array of light emitting diodes and a camera.

This research extends the QR experiments to examine a wide variety of array sizes and coding schemes, and compares each proposed architecture against a realistic channel model. Hypotheses tested involved varying the code scheme, number of lasers, modulation scheme, laser wavelength, detection threshold levels, signal to noise ratio (SNR), and level of turbulence on the channel. The overall expectation was that as SNR and turbulence decreased, any given channel would become increasingly usable. Within this performance curve, increased numbers of lasers combined with increased levels of FEC, should result in more resilient communications with a decrease in efficiency.

Findings and Conclusions

This research applied rigorous simulation testing to several theoretical predictions, and as such, the two principal research areas were divided into coding theory and systems architecture. Data was collected through simulation in both portions, and three basic categories of codes were identified and implemented in software, along with a simulator based on a statistical channel model. Two categories (repetition and Reed-Solomon codes) are found in the literature, and a third category, which combined a temporal channel code with various spatial line codes, was devised for this research. These corresponded to high-, low- and mid-rate codes, respectively. Overall, thirteen different coding schemes were tested during the simulation phase. Previous work using QR codes was also evaluated probabilistically.

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The goal of the systems engineering portion was to identify significant architecture decisions needed to support the development of engineering prototypes. It quantified the significant impact to the system performance of design decisions, including array size, wavelength, modulation scheme, coding scheme, and threshold detection levels, given a range of various atmospheric conditions. These atmospheric conditions included noise and turbulence, and was simulated using the same model as in the coding portion. The systems engineering analysis identified significant main effects and second-degree interactions. Each of the architecture decisions had a statistically significant impact on the system's BER. The irradiance threshold had significant second-degree interactions in concert with the coding scheme, SNR, and the number of lasers. Two additional system measures of performance were the transmission rate and the power efficiency. The tradeoff analysis identified the best performing architectures in terms of BER; within this group, a tradeoff between transmission rate and power efficiency was analyzed to provide the recommended candidate architecture in each turbulence regime.

Our research shows that under weak turbulence conditions, a high-rate coding scheme paired with on-off keying offers the best protection against the minimal effects of the optical channel, while increasing the transmission rate beyond that of a repetition code. As turbulence increases, the code rate must decrease, therefore, in strong turbulence, a repetition code across some level of spatial diversity is required. When implemented accordingly, the impairments of reduced probability of detection, increased probability of the channel being in a fade, and the extended duration of the fades can be overcome.

Recommendations for Further Research

The results of this work identified several opportunities for future research. For example, engineering prototype work to support field testing of these results could explore the ability to employ FSO communications systems under conditions of turbulence and noise. Field programmable gate arrays offer the flexibility to program and develop a system capable of operating at the transmission speeds required in the modern operating environment.

Also, while both portions of this research indicated that large array sizes are required for improved transmission, smaller array sizes may be feasible given a shorter anticipated link length. Other improvements could be made by relaxing the hard-decision requirement and implementing various forms of soft-decision decoding. Convolutional codes were not considered by this research but may prove to be an attractive variable-rate option for the outer code, and low-density parity check codes may also be considered for the outer code. Additionally, algorithmic complexity was not specifically addressed in this research, but future prototyping should take advantage of existing optimizations for several of the codes used.

Implementing interleaving at a greater depth may be useful in low to moderate turbulence cases where the channel is degraded, but not in an outage. If a padding scheme is used to fill the interleaver when data demands are low, interleaving may help overcome the effects of noise at the price of latency, memory and possibly channel overhead. Lastly, inter-layer protocols could be developed to take advantage of the decoding statistics and coordinate retransmission of data prior to transmission-control protocol (TCP) detection of packet failures. This may help obviate the concerns identified by Chan (2006) in which TCP requests significantly affected throughput.

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Acronyms

Bit error rate	BER
Forward error correction	FEC
Free space optical	FSO
Low probability of detection	LPD
Low probability of interception	LPI
s input/multiple output	MIMO
Quick Response	QR
Radio Frequency	RF
Single input/single output	SISO
Signal to noise ratio	SNR
Transmission control protocol	TCP