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Michael Gans, Paul Oleski, Kapil Borle, and Biao Chen

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The prevalent use of unmanned vehicles in military and civilian applications require the existence of robust and high throughput communication with airborne platforms. Real channel measurements are conducted and the analysis supports the use of MIMO communications for such applications due to its potential throughput advantage. Unique challenges and the ways to address them are described in detail. In particular, the lack of scattering and the blockage of line of sight may lead to rank deficient channel matrices, which are exacerbated due to the absence of channel state information at the transmitter. A variable rate MIMO scheme is proposed to overcome these challenges in order to realize the promising throughput gain afforded by the MIMO communication.

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Enhancing Connectivity of Unmanned Vehicles Through MIMO Communications

M. J. Gans and P. J. Oleski
Air Force Research Laboratory
525 Books Road
Rome, NY 13441

Kapil M. Borle and Biao Chen
Dept. of Electrical Engineering and Computer Science
Syracuse University
Syracuse, NY 13244

***Abstract*—The prevalent use of unmanned vehicles in military and civilian applications require the existence of robust and high throughput communication with airborne platforms. Real channel measurements are conducted and the analysis supports the use of MIMO communications for such applications due to its potential throughput advantage. Unique challenges and the ways to address them are described in detail. In particular, the lack of scattering and the blockage of line of sight may lead to rank deficient channel matrices, which are exacerbated due to the absence of channel state information at the transmitter. A variable rate MIMO scheme is proposed to overcome these challenges in order to realize the promising throughput gain afforded by the MIMO communication.**

I. Introduction

The use of autonomous/unmanned vehicles for various civilian and military applications has become increasingly prevalent. The absence of human pilots on board those unmanned systems, however, make it a challenging task to accomplish various intended missions. For example, these unmanned systems are often remotely piloted and thus having a reliable and robust communication link between the aerial systems and the ground control unit is imperative. Even for systems that are semi-autonomous, having a high throughput communication link is often essential to accomplishing any intended mission. Many remote piloted aircrafts (RPAs) are used for surveillance applications and the need to stream surveillance data, including real time video data requires a highly reliable and high-throughput communication link from the RPAs to ground units.

Many legacy communication links (e.g., Link 16 with a data rate not more than 16kb/s) operate at a data rate that becomes highly inadequate for applications where video streaming from aerial systems to ground is needed. Merely scaling up the power/bandwidth is both limited by resource and policy constraints as well as the fundamental theoretical limits dictated by the Shannon theory. A promising technology is the use of multiple antenna communication systems [1]–[3]. The so-called multiple-input multiple-output (MIMO) communication scales up data rate linearly as the number of antennas increase and thus provides great potential for improving the throughput of air to ground communication. This helps enable many envisioned applications that may otherwise be infeasible.

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MIMO communications, however, are traditionally designed for the so-called scattering environment [4] where independent channel variations between different transmit/receive antenna pairs are exploited. For airborne platforms, however, there has been a debate about the feasibility of MIMO communications because of the lack of scattering. However, for certain communication ranges, the large aperture that an aircraft affords makes MIMO an appealing choice of communication that can attain significantly higher throughput given a fixed power/bandwidth budget compared with single antenna systems even in the absence of any scatterers [5].

This paper describes some ongoing research and development effort that uses MIMO communications to enable robust and high capacity connectivity between RPAs and ground terminals. While the large aperture may compensate for the lack of the scattering, two unique challenges still exist for airborne MIMO communications. The large aperture is only attained when antennas are placed strategically apart on a RPA. In the absence of scattering, i.e., when communications are limited by line-of-sight channels, the fact that some antenna elements on a RPA may be completely out of sight from its communicating party may render the channel matrix ill-conditioned. This is further complicated by the high mobility and maneuverability of the RPA which make it infeasible to have complete channel state information (CSI) at the transmitter. To address these challenges, this paper proposes a variable rate MIMO communication scheme that combines the D-BLAST architecture with per antenna spreading to harvest the maximum possible throughput gain allowed by the channel.

The rest of the paper is organized as follows. Section II describes the channel measurement apparatus. The measurement data provides guidance on the potential throughput gain for the particular application of interest as well as challenges in realizing the throughput gain to address these challenges. Section III introduces a modified D-BLAST architecture to address these challenges. Section IV describes simulation results using the real measurement channels to show the potential improvement using the proposed variable MIMO scheme. Section V concludes this paper.

II. MIMO Channel State Matrix Measurements

A. Measurement Apparatus

The process of measuring the channel state matrix at the Newport NY radio range required measuring the complex transmission coefficient from each antenna element on the ground array to each element on the unmanned combat air vehicle (UCAV) model of a RPA. The UCAV is shown in Fig. 1.

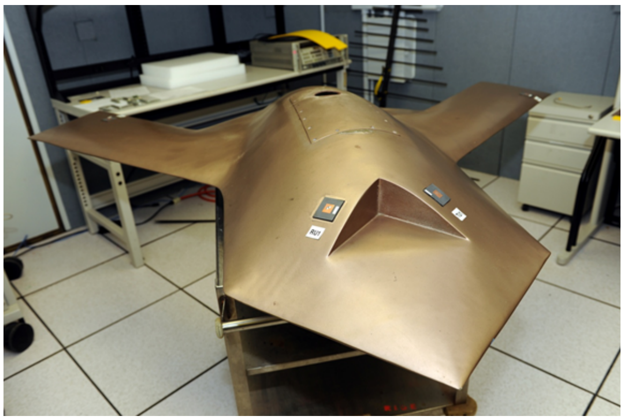
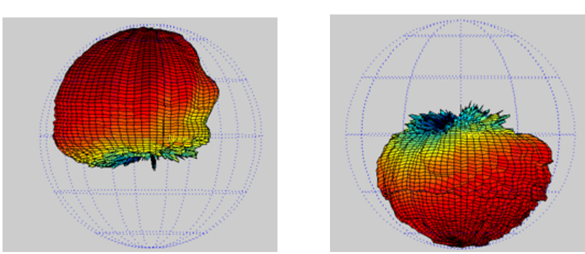


Fig. 1: UCAV with square patch antennas.

The UCAV model was coated with Electrodag to shield the cable networks placed inside the model that connect the patch antennas to the switch which feeds the RF (Radio Frequency) receiver. Although this shielding is not necessary in an operational RPA, it helps, in analyzing the measurements, to restrict the received signals to the patch antennas only. Four patches were installed for the uplink band (at carrier frequency 5.1 GHz with a bandwidth of 100 MHz) and four patches for the downlink band (at carrier frequency of 5.8GHz with a bandwidth of 100 MHz). Each patch has two ports which provide perpendicular linear polarization with about 30 dB cross polarization discrimination (isolation between ports). Thus 8 antenna ports are provided for the uplink and for the downlink, respectively. For easy reference these ports are uniquely labeled. For example, RU12 represents the second port on the first uplink patch on the upper side of the UCAV. The antenna patterns were measured on the Newport Range. Two such power patterns are shown in Fig. 2a and 2b.

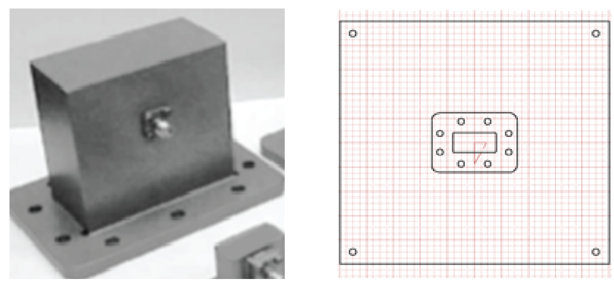


(a) Antenna RU11 (b) Antenna RU31

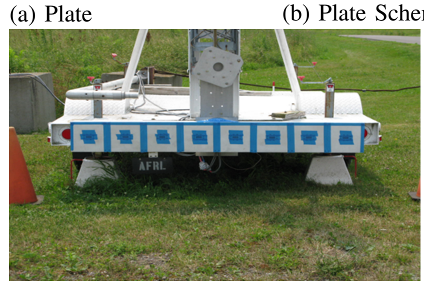
Fig. 2: Antenna Pattern

The power pattern for antenna RU11 gives pretty good coverage above the UCAV because it is on the upper surface of the UCAV. Antenna RL31 is on the bottom surface of the UCAV wing and has good coverage in the hemisphere below the UCAV but is weak above the UCAV. These patterns emphasize the need for the diagonal BLAST form of MIMO in order to provide full coverage for all data streams.

The ground array utilizes coax-to-waveguide adapters as antenna elements. They provide wide angular coverage (110^o E-Plane and 80^o H-Plane) and wide bandwidth 4.9 GHz to 7.05GHz. The array is mounted with square plates as shown in Fig. 3. The square plates allow a choice of vertical or horizontal polarizations. Typically measurements are made with all vertically polarized antenna elements or with polarizations alternated between vertical and horizontal polarization to see the effect of polarization mixing on MIMO capacity. The elements can be at various spacing by bolting the plates to different positions along the mounting rails. The spacing shown in Fig. 3 provide an 80 inch wide array. Another test used a 30 foot wide array. The array is mounted on an expanding tower which allows array heights of 2 feet to 40 feet above ground level.



(a) Plate (b) Plate Schematic



(c) Ground Array

Fig. 3: Element Ground Array

The UCAV is mounted on a positioning tower at a height of 70 feet. The position of the UCAV can be rotated around a vertical axis (relative to ground) for 360 degrees of azimuth. It can also be rotated in pitch and roll over 90. The UCAV support is provided by an absorber covered arm from the top or bottom of the UCAV. A view of the 400 foot range at Newport showing the UCAV and the ground array is shown in Fig. 4. It is seen that the range is relatively free of scattering, so that the MIMO performance should be similar to free space limitations.

The switch at the ground array cycles through the 8 elements in a 20 millisecond period. After each of the ground array

Fig. 4: UCAV and Ground Array on the 400 ft. Newport Range.

cycles, the switch at the UCAV connects to a new antenna port of the 16 UCAV antenna ports. As this switching is completed the azimuth turntable moves to a new position for a given pattern cut. At each position of the cut, the complex transmission coefficient from each antenna element on the ground array to each element port on the UCAV is recorded. The frequency and pitch and yaw positions can be modified for new cuts.

B. Challenges

Fig. 2a and 2b illustrate the unique challenges of airborne MIMO. Each antenna element has only limited visibility for communication, depending on the orientations of the transceiver pair. This is further exacerbated by the lack of channel state information at the transmitter - RPAs are not only of high mobility but they may maneuver in-flight which make it infeasible to constantly feedback channel state to the transmitter.

Nevertheless, the channel matrices indicate that there exist significant theoretical throughput improvement through MIMO communications if designed properly. In the following, we describe a simple variable rate MIMO scheme to address the above mentioned challenges. We demonstrate through numerical simulation that the proposed scheme is capable of overcoming the above challenges and realizing significant performance gain.

III. Variable Rate MIMO

While the channel matrix measurements exhibit potential for significant throughput improvement via MIMO communications, significant challenges exist that need to be overcome in order to realize this potential. In particular, the lack of scattering makes the channel susceptible to ill-conditioning when antenna elements may be out of sight to the communicating party. In the absence of complete CSI at the transmitter, there is a need to ensure that any independent data stream is not stuck with an antenna element that is out-of-sight. This makes D-BLAST a very natural candidate for such applications. D-BLAST (Diagonal Bell Lab Layered Space Time) is an outage optimal transceiver architecture for MIMO communication system [1], [4]. The architecture essentially involves independent coding and modulation of N data streams and rotating each stream through all the transmit antennas. Here, N is the number of transmit antennas. The rotation is performed in a way that makes sure that each stream experiences the channel from all the transmit antennas and all levels of interference *i.e.,* no interference to experiencing interference from all of the other $N-1$ streams at the receiver as each stream rotates in the space-time domain.

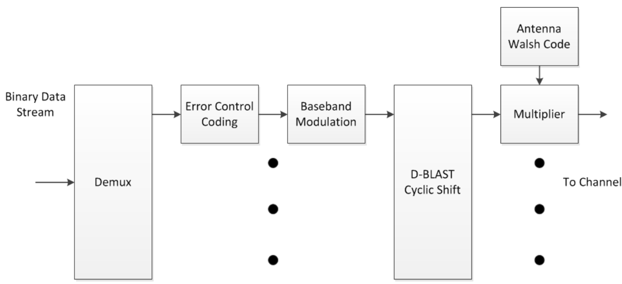
The verbatim application of D-BLAST, however, is still inadequate when channel matrices are highly ill-conditioned. The existence of antennas that experience channel outage due to blockage will drag down the overall performance. From a theoretical viewpoint, the independent data streams accommodated in a MIMO channel should be no larger than the effective rank of the matrix. The challenge is, in the absence of complete CSI at the transmitter, how to utilize the advantage of D-BLAST while being able to handle the potential rank deficiency of channel matrices.

We propose a simple scheme of variable rate MIMO - the variable rate is not only achieved though the traditional means of controlling the coding rate as well as modulation order, but the number of independent data streams is also adapted through per antenna spreading. The modified D-BLAST architecture is illustrated in Fig. 5. Without loss of generality, we assume the MIMO system has N transmit and N receive antennas. At the transmitter side, spreading is done on a per antenna basis with a length M Walsh code for each antenna where $M < N$. As such, a group of N/M antennas will share the same Walsh code and the effective number of data streams is reduced to N/M. At the receiver side, de-spreading is embedded in the D-BLAST receiver to facilitate successive interference cancellation.

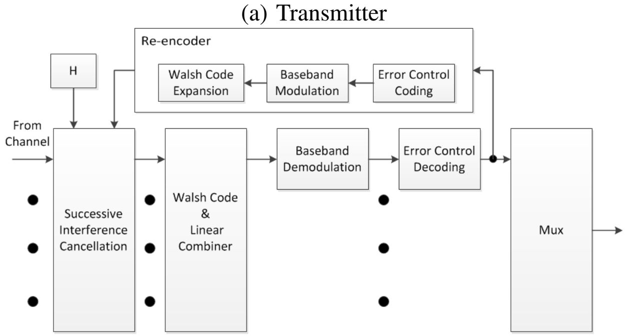
As an illustration, consider a 8×8 MIMO system. Let $a_0, a_1, \ldots, a_7$ denote the 8 transmit antennas. Let each symbol from any 4 antennas, say a_0, a_1, a_2, a_3 be spread by $[1\ 1]^T$. Similarly, let each symbols from the remaining 4 antennas, a_4, a_5, a_6, a_7 be spread using $[-1\ 1]^T$. Notice that $[1\ 1]^T$ and $[-1\ 1]^T$ are orthogonal to each other. At the receiver, de-spreading effectively reduces the number of mutually interfering streams from 8 to 4.

The illustration in the previous paragraph implicitly assumes that the transmitter and the receiver have agreed on some spreading factor, M, and the corresponding Walsh codes. As the transmitter does not possess any CSI, our assumption holds true only if there exists a very low rate feedback link from the receiver to the transmitter. The receiver, which knows the CSI, can feedback the spreading factor to the transmitter, which then can adapt the transmission strategy to the channel conditions. For example, in the 8×8 case, one need a total of 2 bits for the spreading factor of 1 (no spreading), 2, 4, and 8 where the last one corresponds to essentially a beamforming strategy.

In the next section we simulate the variable rate MIMO scheme over measured channels to examine the performance of the proposed variable rate MIMO D-BLAST for low rank channels.



(a) Transmitter



(b) Receiver

Fig. 5: Variable rate MIMO transceiver block diagram

IV. Simulation

We assess the performance of the variable rate D-BLAST scheme by comparing it with the orignial D-BLAST for the following two channel measurement configurations.

- All Vertical Polarization (VP).
- Mixed Polarization (MP).

As mentioned earlier, we are motivated to use VP and MP to see the effect of polarization mixing on MIMO capacity. The channels obtained using VP tend be rank deficient. On the other hand, channels obtained using MP tend to have a higher rank than that of VP. This is because the two polarizations effectively serve to create two orthogonal channels. This leads to more well-conditioned MP channel matrices than the corresponding VP ones.

For each of the above two configurations we have obtained about 13000 channel measurements, each of which corresponds to a unique combination of azimuth and elevation. During simulation, we select 10% of the channels at random, and measure the average outage over these channels.

Fig. 6 compares the outage behavior of the variable rate D-BLAST scheme with the original D-BLAST at a fixed rate of 4 bits/s/Hz. The variable rate D-BLAST scheme uses a spreading factor of 2, QPSK modulation and $1/2$ rate LDPC code. While the D-BLAST scheme uses BPSK modulation and $1/2$ rate LDPC code. Clearly, at low outage probabilities, the variable rate D-BLAST scheme provides an SNR gain of about 4 dB over the original D-BLAST.

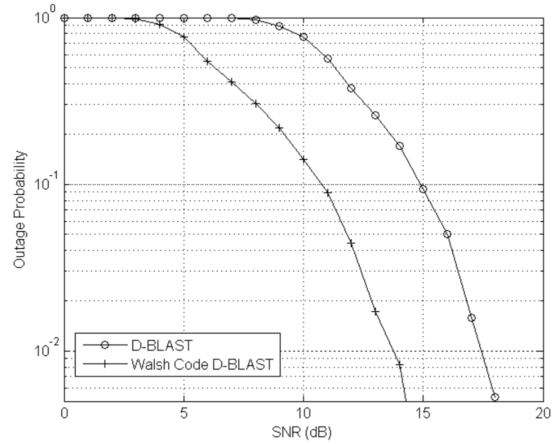


Fig. 6: Outage rate for all vertical polarization at rate 4 bits/s/Hz.

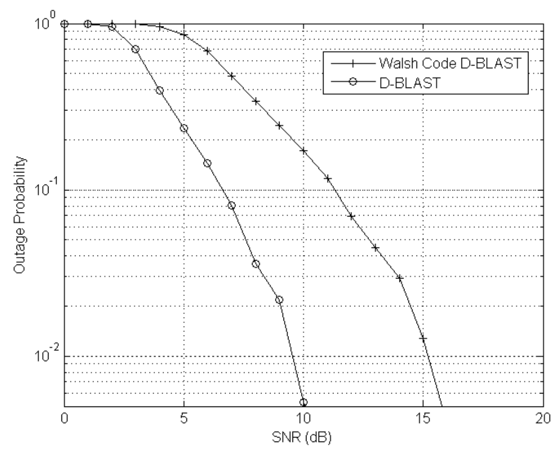


Fig. 7: Outage rate for mixed polarization at rate 4 bits/s/Hz.

Fig. 7, on the other hand, shows that the variable rate D-BLAST scheme is inefficient for mixed polarization channels. The original D-BLAST outperforms variable rate D-BLAST by about 6 dB SNR at low outage probabilities.

The above simulation results show that for the low rank channel matrices obtained by only vertical polarization, the variable rate D-BLAST scheme outperforms D-BLAST, while for well conditioned channel matrices, the original D-BLAST architecture suffices.

V. Conclusion

In this paper we have introduced a new scheme to transmit data over MIMO channels which may be ill-conditioned. In the absence of channel state information at the transmitter the scheme overcomes this challenge by per antenna spreading in the D-BLAST architecture, thereby effectively reducing the number of independent data streams. Using real measurement channels we demonstrated through simulations that one can achieve significant SNR gain over the original D-BLAST for rank deficient channel matrices.

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