Unsupervised Detection via Artificial Dual-Path Transmission

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***Abstract*—Channel estimation in rapidly time-varying or short and bursty communication scenarios is costly in terms of both pilot overhead and co-channel interference. In recent work, it was shown that multipath delay-diversity can be exploited to detect multiple co-channel user signals, provided that the relative multipath delays for the different users are distinct, and the two multipath 'taps' of each user have roughly commensurate power. These requirements may not hold naturally, however, especially for relatively narrowband or short-range transmissions with small delay spread. As an alternative, this paper advocates using dual-antenna transmission in a manner that introduces artificial multipath and tight control of the power of the two channel taps, via baseband processing at the transmitter. The approach enjoys theoretical guarantees and affords simple decoding and accurate synchronization as a side bonus. Similar claims have been previously laid using packet repetition via a single transmit-antenna, but the dual-antenna artificial multipath scheme proposed herein doubles the transmission rate relative to packet repetition. Laboratory experiments using programmable radios are used to demonstrate successful operation of the proposed transmission scheme in practice.**

***Index Terms*—Path diversity, canonical correlation analysis, multiple-input multiple-output (MIMO), wireless communication, unsupervised detection, unsupervised sychronization.**

I. Introduction

As the wireless landscape expands to include a plethora of beyond-5G technologies and WiFi-enabled Internet of Things (IoT) devices, there is an increasing need for high-rate and low-latency communication over time-varying channels [1]. Not only are more devices sharing bandwidth, but data intensive services – e.g., high definition video calling or streaming, mobile virtual reality, or vehicle-to-everything (V2X) – are becoming increasingly commonplace. Rapidly time-varying channels and bursty communication, common in IoT and mobile scenarios, make channel estimation difficult due to the pilot transmission overhead, which can be a significant fraction of the payload.

Unsupervised machine learning techniques have evolved as a means to overcome channel estimation issues [2], [3]. For instance, canonical correlation analysis (CCA), a widely-used machine learning tool, has proven itself successful in solving a wide range of challenging wireless communication problems in an unsupervised manner. This includes, but is not limited to, equalization [4], blind source separation [3], [5], and cell-edge user detection [6]. In its simplest form, CCA seeks to find two linear combinations of two random vectors that yield a pair of maximally correlated random variables [7], [8]. An algebraic interpretation of CCA was recently provided, which shows that CCA discovers the "shared" subspace between two matrix views, and that this subspace can be identified even if the "unshared" subspaces of the two matrices are dominant, even by orders of magnitude [2].

In this paper, we aim to bypass the channel estimation stage entirely, by designing the transmission line code to enable unsupervised detection at the receiver, thus avoiding issues like pilot contamination [9], [10] or fast channel variation, and enabling short and bursty transmission. We propose and experimentally verify a dual-antenna artificial multipath transmission scheme that improves upon our previous work by doubling the transmission rate relative to [11], which utilized CCA in the context of spectrum underlay to allow a pair of secondary users to reliably communicate in underlay mode while keeping the interference at a primary receiver close to its noise floor. The main idea of [11] is to use repetition coding at the secondary single-antenna transmitter to enable CCA decoding at the secondary receiver, which can recover the secondary packet even in the presence of very strong interference from the primary user. In contrast, by judiciously overlapping the two packet replicas and using dual-antenna transmission, the present paper is able to double the transmission rate while still maintaining the ability of CCA to correctly decode the desired low-power signal, even in the

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presence of strong interference. In another recent work [12], we leveraged multiple independently delayed and faded copies of each transmitted signal in a multiuser context. If each user's signal is received through two (or more) distinct paths at different times, then the relative path delays and the user signals can be identified via CCA [12]. Relative to [12], our present work does not rely on the propagation medium to fortuitously provide two transmission paths having distinguishable delays and phase shifts but roughly commensurate path losses. Instead, we create these opportune circumstances through the proposed transmission protocol.

The rest of this paper is organized as follows. Section II sets forth the discrete-time baseband-equivalent system model and introduces the problem in technical terms. Section III explains the proposed dual-path transmission scheme, while Section IV lays out the proposed CCA-based detector. Section V presents our experimental results, which were all obtained in the lab, using programmable software radios to implement the proposed scheme and test its performance in practice. As a bonus, we also show in this section how the proposed transmission protocol / line code structure can be exploited to enable accurate and pilot-less symbol timing and carrier frequency offset synchronization. We present lab experiments to showcase this side-benefit as well.

II. System Model and Problem Statement

Consider a MIMO communication scenario comprising a transceiver pair communicating over a narrowband channel (or consider a single subcarrier, in the case of multicarrier modulation). The transmitter (Tx) is equipped with $M_t \geq 2$ antennas while the receiver (Rx) is equipped with $M_r \geq 2$ antennas. The communication between the Tx and Rx nodes may occur in the presence of unknown and possibly time-varying interference. Let $\mathbf{x}(n) := \sqrt{\alpha}\mathbf{v}s(n) \in \mathbb{C}^{M_t}$ denote the precoded transmitted signal, where $s(n) \in \mathbb{C}$ is the n-th transmitted (digital or analog) symbol (Tx sample), for $n = 1, \cdots, N$, $\mathbf{v} \in \mathbb{C}^{M_t}$ represents the precoder used at the Tx, and α controls the transmit power. The received baseband-equivalent model of the multiantenna signal $\mathbf{y}(n) \in \mathbb{C}^{M_r}$, is given by

$$\mathbf{y}(n) = \mathbf{H}\mathbf{x}(n) + \mathbf{p}(n) + \mathbf{w}(n) \tag{1}$$

where $\mathbf{H} \in \mathbb{C}^{M_r \times M_t}$ denotes the channel between the Tx and Rx, $\mathbf{w} \in \mathbb{C}^{M_r}$ is the noise term with i.i.d entries of zero mean and variance σ^2 each, and $\mathbf{p} \in \mathbb{C}^{M_r}$ represents the interference term. Note that the power control factor has been absorbed in the channel matrix for brevity.

The goal is to reliably recover the transmitted signal $\mathbf{s} := [s(1), \cdots, s(N)]^T \in \mathbb{C}^N$ in an unsupervised manner, at modest/low SNR levels, and without imposing any structure on the transmitted signal. To do so, we will next propose a simple dual-path transmission scheme in a way that induces an artificial multipath effect. Then, exploiting the induced multipath at the Rx, it will be shown that the Rx can employ CCA to detect the information-bearing signal without knowing the channel $\mathbf{H}$ or any interference-related information.

III. Dual-Path Transmission Scheme

In this section, we introduce a simple dual-path transmission scheme that will be later exploited at the receiver to enable unsupervised detection. The proposed scheme relies on delay diversity, a form of diversity where the signal $\mathbf{x}(n)$ is transmitted twice in space via introducing artificial delay. Each transmission is differently precoded and delayed from the previous transmission by n_0 symbols, where n_0 is known (pre-agreed upon) at the receiver[1]. In particular, We propose the following design of the transmitted signal,

$$\mathbf{x}(n) = \sqrt{\alpha_1}\mathbf{v}_1 s(n) + \sqrt{\alpha_2}\mathbf{v}_2 s(n - n_0) \tag{2}$$

where n_0 is the artificial delay introduced at the Tx and is assumed to be known at the Rx, α_1 and α_2 are the allocated power for the precoded signal and its delayed precoded version, respectively. In this work, we assume that the precoders $\mathbf{v}_1$ and $\mathbf{v}_2$ are selected as columns of the DFT matrix. However, the method can work with any selected (distinct) precoders.

One striking difference between the proposed approach compared to the one in [12] is that the design in (2) allows splitting the allocated power evenly between the original signal and its delayed version, making the CCA approach more effective relative to the typical power-imbalanced scenario in a natural multipath environment as considered in [12]. Namely, the first (direct) path is usually considerably stronger than the second (reflected) path in a natural multipath environment, and this imbalance has a bearing on the performance of CCA. This ability to equalize the power of the two artificial paths will make CCA work better in our present context relative to the setting in [12].

Substituting the transmitted signal (2) into (1), one can rewrite (1) as

$$\mathbf{y}(n) = \mathbf{h}_1 s(n) + \mathbf{h}_2 s(n - n_0) + \mathbf{p}(n) + \mathbf{w}(n) \tag{3}$$

where $\mathbf{h}_1 := \mathbf{H}\mathbf{v}_1$ and $\mathbf{h}_2 := \mathbf{H}\mathbf{v}_2$ are defined as the effective channel vectors associated with the transmitted signal and its delayed version. Next, we will show

[1]The proposed approach can still work if n_0 is unknown at the receiver, as we will see.

how the designed transmission scheme will help the receiver to decode the desired signal without estimating the channel.

IV. Proposed Detector

In order to reliably decode the desired signal at the receiver, we use an algebraic version of CCA. In its plain form, CCA is a machine learning technique that seeks to find two linear combinations of random vectors $\mathbf{y}_1 \in \mathbb{C}^{M_1}$ and $\mathbf{y}_2 \in \mathbb{C}^{M_2}$ such that the resulting pair of scalar random variables is maximally correlated [7], [8]. Assuming that N realizations of the random vectors $\mathbf{y}_1$ and $\mathbf{y}_2$, i.e., $\mathbf{Y}_\ell = [\mathbf{y}_\ell[1], \cdots, \mathbf{y}_\ell[N]] \in \mathbb{C}^{M_1 \times N}$ for $\ell = 1, 2$, are available, the CCA problem can be expressed as [8],

$$\min_{\mathbf{q}_1, \mathbf{q}_2} \|\mathbf{Y}_1^H \mathbf{q}_1 - \mathbf{Y}_2^H \mathbf{q}_2\|_2^2 \tag{4a}$$

$$\text{s.t.} \quad \mathbf{q}_\ell^H \mathbf{Y}_\ell \mathbf{Y}_\ell^H \mathbf{q}_\ell = 1, \quad \ell = 1, 2, \tag{4b}$$

Problem (4) is referred to as the distance minimization formulation of CCA. It aims at finding two vectors $\mathbf{q}_1 \in \mathbb{C}^{M_1}$ and $\mathbf{q}_2 \in \mathbb{C}^{M_2}$, such that the Euclidean distance between the resulting vector realizations is minimized. An alternative and equivalent formulation of (4), in the two views case, is to look for a common/shared low-dimensional subspace $\mathbf{g} \in \mathbb{C}^N$ of the two data views $\mathbf{Y}_1$ and $\mathbf{Y}_2$. This can be posed as

$$\min_{\mathbf{g}, \mathbf{q}_1, \mathbf{q}_2} \sum_{\ell=1}^{2} \|\mathbf{Y}_\ell^H \mathbf{q}_\ell - \mathbf{g}\|_2^2, \tag{5a}$$

$$\text{s.t.} \quad \|\mathbf{g}\|_2^2 = 1, \tag{5b}$$

which is referred to as the maximum-variance (MAX-VAR) formulation of CCA [13]. Problem (5) admits a relatively simple algebraic solution, rendering the method computationally appealing for practical implementation. Specifically, the optimal solution $(\mathbf{q}_1^\star, \mathbf{q}_2^\star, \mathbf{g}^\star)$ of (5) can be obtained via eigendecomposition of a matrix that involves three correlation matrices and two small matrix inversions.

We recently formulated a new interpretation of CCA from an algebraic viewpoint [14]. In particular, we showed that, in the noiseless case, given two multi-antenna signal views with strong individual components per view and a weak shared component, CCA will recover the shared component no matter how strong the individual components are. We also developed a companion performance analysis that ensures the reliable detection of the common signal via CCA is possible at low SNR/SINR [2].

Building upon these findings, we will now show how to decode the desired signal given the received signal in (3). Assuming that the artificial delay n_0 is known at the receiver, one can use n_0 to create two signal views from the received signal in (3), which can be written in more compact form as,

$$\mathbf{Y}_1 = \mathbf{h}_1 \mathbf{s}^T + \mathbf{P}_1 + \mathbf{W}_1 \tag{6}$$

$$\mathbf{Y}_2 = \mathbf{h}_2 \mathbf{s}^T + \mathbf{P}_2 + \mathbf{W}_2 \tag{7}$$

where $\mathbf{W}_\ell$ and $\mathbf{P}_\ell$ are the noise term and interference term associated with the ℓ-th view, for $\ell = 1, 2$. Note that the two views in (6) and (7) share one common component which is the information-bearing signal of interest while the interference is naturally different in the two views. Now applying CCA to the two constructed views in (6) and (7), our theoretical results [2] dictate that the signal of interest can be identified in the noise-free scenario regardless of how strong the interfering terms are (i.e., $\mathbf{P}_1$ and $\mathbf{P}_2$). For instance, if we model the interference as the sum of L rank 1 transmissions, where L is the number of active interferers, then we can have the following recovery claim which is similar to the one in [2] with slight modifications.

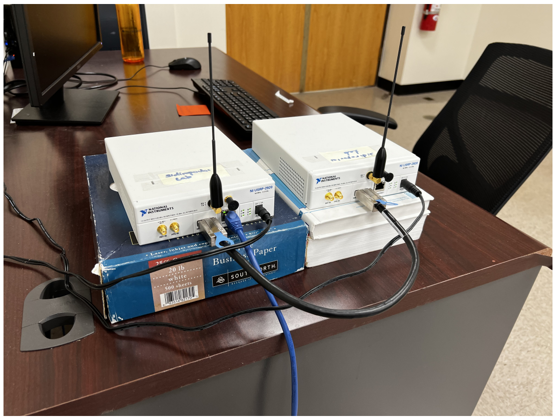
Theorem 1. *In the noiseless case, if the matrix* $\mathbf{B}_i \in \mathbb{C}^{N \times (L+1)}$*, and* $\mathbf{H}_i \in \mathbb{C}^{M_r \times (L+1)}$ *are full column rank matrices holding the transmitted sequences and the effective channel matrices, respectively, then the optimal solution* $\mathbf{g}_i^\star$ *of problem* (5) *is given by* $\mathbf{g}^\star = \gamma \mathbf{s}$*, where* $\gamma \in \mathbb{C}$*,* $\gamma \neq 0$ *is a complex scaling factor.*

Proof. The proof follows from Theorem 1 in [2]. □

As a side benefit of the proposed framework, we can use the proposed dual-path transmission scheme for timing and carrier frequency offset (CFO) synchronization as we will show in the experiments in Section V. In particular, we track the CCA correlation coefficient (objective of (5)) over a two-dimensional window of time and CFO ranges. Then, it can be seen that the CCA correlation coefficient will peak when we hit the right timing and CFO. Otherwise, incorrect timing and/or CFO will lead to uncorrelated signals in the two views, assuming that the transmitted symbol sequences are zero-mean white.

V. Experimental Results

To experimentally verify our proposed method, we established a 2×2 lab setup which uses four National Instruments USRP-2920 software-defined radios as shown in Figure 1. The transmitter has two radios, each representing a separate antenna, connected by a MIMO cable to allow timing synchronization. The same setup exists at the receiver with a MIMO cable that



(a) Transmitter

(b) Receiver

Fig. 1: Transmitter and receiver setups used to conduct experiments. Note that the antennas at both the transmitter and receiver are synchronized using MIMO cables.

allows both timing and CFO synchronization across the two antennas. We assume QPSK-modulated packets with the packet length set to $N = 256$. An artificial delay of 10 symbols (known at the receiver) is introduced. Further, we use DFT based precoding where the two precoders $\mathbf{v}_1$ and $\mathbf{v}_2$ are chosen from the DFT matrix normalized by $1/\sqrt{M_t}$. Both Tx antennas transmit with 15 dB antenna gain. At the receiver, the transmissions are received with an antenna gain of 25 dB, after which they are processed using the steps outlined in Section IV.

Tx Power (dBm)	Avg SER Over 1000 Packets
10	0.00128549
5	0.00142915
3	0.00235044
1	0.00312399
-3	0.07737538

TABLE I: Average SER over 1000 processed packets for specified transmit powers.

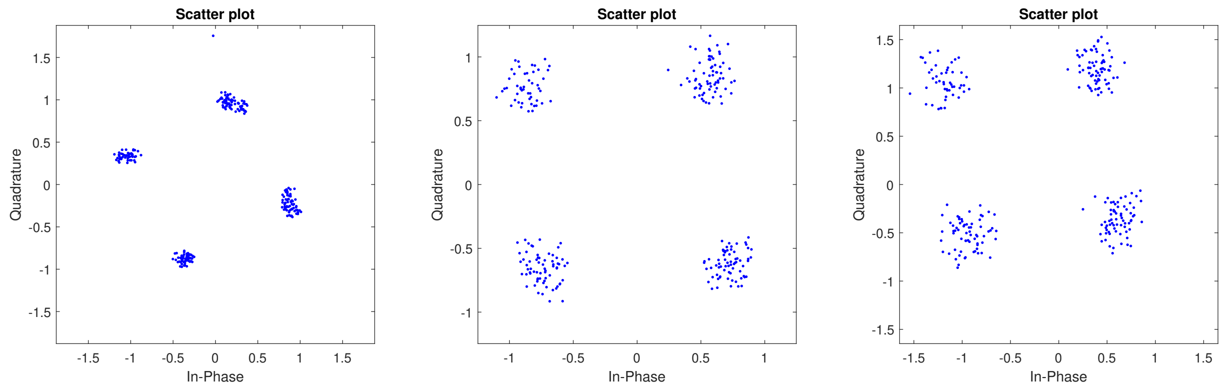
Figure 2 displays scatter plots of received packets corresponding to transmit powers of 10, 1, and -3 dBm. After the packets are processed, the symbol error rate (SER) is calculated and listed next to the corresponding transmit power level in Table I. As expected, the packets are more tightly clustered at higher transmit powers, as is clear when comparing Figures 2(a) and 2(c).

A note on synchronization. We employed the built-in CFO correction, since there is only one CFO here due to the MIMO cables. On the other hand, the start of the first packet was detected using CCA to serially search for high canonical correlation with the known n_0. We did not use any pilots for synchronization; we only used a single pilot for phase correction. The same line-code structure can also be exploited to detect the right n_0, albeit this requires 2-D (packet start time, n_0) search. To verify this, we fixed the packet start time, varied n_0, and calculated the canonical correlation between the two views for a range of values for n_0. We conducted five trials of this experiment in the lab, at 3 dBm transmit power, and the results are plotted in Figure 3. This shows that CCA can also be used to detect the correct n_0.

VI. Conclusions

In this paper, we bypassed the channel estimation stage by designing a transmission line code to enable unsupervised detection at the receiver in order to avoid issues like pilot contamination. We proposed and experimentally verified a dual-antenna artificial multipath transmission scheme which takes advantage of delay diversity. Two transmissions are used at the transmitter, and each transmission is differently precoded and delayed from the previous transmission by a certain number of symbols known at the receiver. Then, exploiting this new transmitted signal structure at the receiver, it was shown that the Rx can employ CCA to detect the signal without knowing the channel $\mathbf{H}$ or any interference-related information. The proposed approach allows splitting of the allocated power evenly between the original signal and its delayed version, making this CCA approach efficient in a natural environment. As a side benefit, we also used the proposed dual-path transmission scheme for synchronization purposes. This scheme allowed us to reliably recover the transmitted signal in an unsupervised manner, at modest/low SNR levels, and without imposing any redundancy / error-control structure on the transmitted signal.

In order to validate the proposed framework, we presented experimental results from a wireless testbed in our lab, using software-defined radios to demonstrate the advantages of the proposed dual-path setup in practice.



(a) 10 dBm (b) 1 dBm (c) -3 dBm

Fig. 2: Scatter plots of packets at specified transmit powers for QPSK modulation.

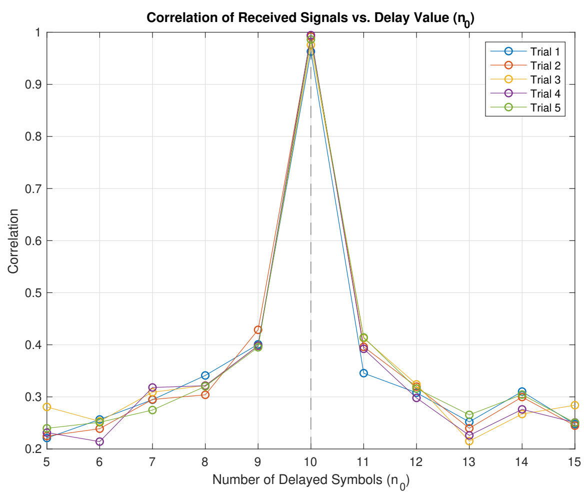


Fig. 3: Canonical correlation coefficient between the two received views with varying delay value n_0 at the receiver. Note the particularly high correlation for $n_0 = 10$, which is the correct delay. Five curves corresponding to five live trials conducted at 3 dBm transmit power to assess variability.

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