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BLIND IDENTIFICATION FOR FIXED FRAGMENT-SIZE PACKET TRANSMISSIONS WITH DISTRIBUTED REDUNDANCY OVER MULTIPATH FADING CHANNELS

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ABSTRACT

Standardized wireless transmissions include fixed-size fragments per packet. Relying on this structure, two schemes for distributing redundancy across fragments are considered in this paper to enable blind identification without higher-order statistics of received signals. We prove that both schemes guarantee blind identifiability as well as symbol detectability and propose a subspace based blind identification method. We test their relative merits, and compare them with existing alternatives using simulations.

1. INTRODUCTION

Block transmissions relying on linear redundant precoding with cyclic prefix (CP) or zero padding (ZP) guards have gained increasing interest recently for mitigating frequency-selective multipath effects; see e.g., [1, 3, 9, 10] and references therein. Sufficient redundancy removes inter block interference (IBI), and facilitates even blind acquisition of channel state information at the receiver. It also leads to data efficient low-complexity linear equalizers (zero-forcing (ZF) or minimum mean-squared error (MMSE)) with guaranteed constellation-irrespective symbol detectability regardless of the zero locations of the underlying finite impulse response (FIR) channel [9]. Guaranteed symbol detectability implies full multipath diversity, and thus improved performance at moderate-high SNR [11, 12].

To take advantage of these benefits in e.g., ZP transmissions, the number of padded-zeros should be longer than the underlying FIR channel order. But in order to avoid severe bandwidth efficiency loss with long channels, this calls for longer block sizes, which in turn leads to higher decoding delay and decoding complexity. In many protocols however, such as the IEEE 802.11a, the fragment of a packet constitutes the size-invariant transmission unit, that is fixed *a priori*, and is not allowed to change depending on the realization of the random wireless fading channel. Selecting guard sizes for the longest possible channel is one approach, but it is certainly conservative. Instead, the approach pursued in this paper is to have fixed fragment size packet transmissions with redundancy distributed across fragments.

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In [7], two transmissions have been proposed that utilize zero-padded information bearing fragments per packet, which enjoy benefits of ZP block transmissions, if the number of zeros is greater than the channel order. If not, we either transmit a controllable number of null fragments, or, we re-transmit a certain number of information bearing fragments. In other words, we either zero pad fragments per packet, or we cyclic prefix fragments per packet. Because either way the redundancy is distributed across fragments, the two schemes are termed distributed ZP (D-ZP) and distributed CP (D-CP), respectively. Both maintain the fragment size, but D-CP maintains also the fragment structure.

For coherent detection, channel state information is required at the receiver for linear equalization. Usually, training sequences are needed to acquire it but transmitting training sequences reduces bandwidth efficiency. Blind schemes without training sequences offer bandwidth-efficient alternatives, e.g., [2, 4, 5, 9]. We prove that blind identification is possible both for D-ZP and D-CP without higher-order statistics. We develop a subspace based blind channel identification method similar to the method for the original ZP transmissions developed in [9]. Simulation examples illustrate their relative merits, and compare them with the original ZP transmissions.

2. MODELING AND PRELIMINARIES

We consider point-to-point wireless transmissions over time-flat but frequency-selective fading channels. The corresponding baseband equivalent model is depicted in Fig. 1.

At the transmitter, the information-bearing sequence $\{s(n)\}$ is parsed into blocks $\boldsymbol{s}(n) = [s(Mn), \ldots, s(Mn + M)]^T$ of size M. To mitigate the effects of frequency selective channels, we pad N_0 zeros at the end of each block to obtain zero-padded (ZP) transmitted fragments $\{\boldsymbol{u}(n)\}$ of size $N := M + N_0$ (Fig. 2), as in [10].

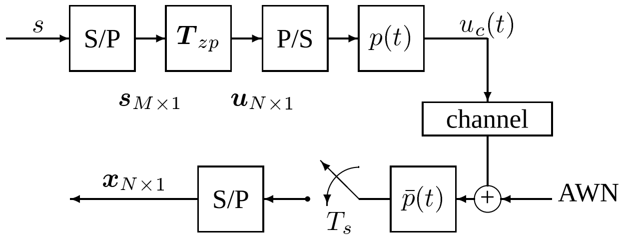

Fig. 1. A schematic diagram for block transmissions

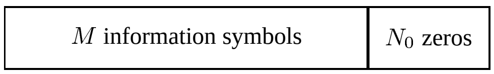

Fig. 2. A fragment

The ZP fragments can be described in matrix form as

$$\boldsymbol{u}(n) = \boldsymbol{T}_{zp}\boldsymbol{s}(n), \tag{1}$$

where the $(M+N_0)\times M$ zero-padding matrix $\boldsymbol{T}_{zp}$ is given by

$$\boldsymbol{T}_{zp} = \begin{bmatrix} \boldsymbol{I}_M \\ \mathbf{0}_{N_0\times M} \end{bmatrix}, \tag{2}$$

with $\boldsymbol{I}_M$ denoting the identity matrix of size M, and $\mathbf{0}_{N_0\times M}$ the $N_0 \times M$ zero matrix. A ZP fragment is considered as the fundamental transmission unit. Each fragment is parallel-to-serial (P/S) to $\bar{u}(k)$, digital-to-analog (D/A) converted, and pulse-shaped to yield the continuous-time signal $u_c(t) = \sum_{k=-\infty}^{\infty} \bar{u}(k)p(t-kT_s)$, where $p(t)$ denotes the transmit filter, and T_s stands for the symbol period.

Let $h_c(t)$ denote the overall impulse response of the transmit-filter, the continuous-time channel, and the receive-filter. With $\tau_{\max}$ denoting the maximum delay spread of $h_c(t)$, our discrete-time baseband equivalent FIR channel, $h(n) := h_c(nT_s)$, has order $L = \lceil \tau_{\max}/T_s \rceil$, where $\lceil \ \rceil$ stands for integer-ceiling. The FIR channel $h(n)$ is considered linear time-invariant over a number of fragments that comprise a packet.

At the receiver, we assume perfect timing and carrier synchronization and sample the output of the front-end filter $\bar{p}(t)$ (that is matched to the transmit-pulse) at the symbol rate $1/T_s$. We collect $N(= M+N_0)$ noisy samples in a $N\times 1$ received vector $\boldsymbol{x}(n)$. If the number N_0 of redundant zeros in each block is greater than or equal to the channel order L, i.e., $N_0 \geq L$, interblock interference (IBI) is removed, and we obtain,

$$\boldsymbol{x}(n) = \boldsymbol{H}_{tr}\boldsymbol{s}(n) + \boldsymbol{v}(n), \tag{3}$$

where $\boldsymbol{H}_{tr}$ is a tall $N \times M$ (truncated) Toeplitz matrix with first column $[h(0), h(1), \ldots, h(L), \mathbf{0}^T]^T$ and first row $[h(0), \mathbf{0}^T]$, which has always full column rank, unless the channel is null [10].

Although redundant zeros reduce the bandwidth efficiency to $M/(M+N_0)$, if $N_0 \geq L$, several benefits become available with ZP:

1. low-complexity block-by-block processing with e.g., linear ZF or MMSE equalization, at the receiver [10];

2. irrespective of the constellation, symbols can be detectable with linear equalizers regardless of the channel zero locations in the absence noise (symbol detectability) [11];

3. full multipath diversity gain is enabled to enhance system performance (maximum diversity advantage) [11, 12];

4. blind identification of the unknown channel becomes possible [9].

However, as soon as the guard interval is shorter than the channel order, i.e., $N_0 < L$, these properties may be lost. In a nutshell, the selection of M and N_0 affects: i) performance (by altering the diversity advantage); ii) bandwidth efficiency (by changing the ratio $M/(M+N_0)$; iii) blocking and decoding delay, as well as decoding complexity (via the frame size $N := M + N_0$).

The maximum order, call it $L_{\max}$, of a wireless propagation channel can be estimated experimentally. One may then select the number of redundant symbols $N_0 \geq L_{\max}$ to remove IBI of possible channel realizations. But this is a conservative approach, because it reduces bandwidth efficiency for channel realizations having order $L \ll L_{\max}$. This observation prompted us to consider transmissions with controlled redundancy, that can be added in a distributed fashion. In [7], *fixed fragment size packet* transmissions with *redundancy distributed* across fragments are proposed, capable of handling channels with long impulse response, while enjoying the performance benefits of ZP transmissions with low decoding complexity. However, their blind identifiability was not addressed. Our goal in this paper is to develop blind identification for fixed fragment size packet transmissions with redundancy distributed across fragments.

3. PACKETS WITH DISTRIBUTED REDUNDANCY

Now we introduce fixed fragment size packet transmissions with redundancy distributed across fragments [7]. With an upper bound of the channel order available both at the transmitter and at the receiver, we consider packet transmissions with the short (e.g., $N \leq 10$) ZP fragments described in the previous section. Each packet consists of N_f information-bearing fragments, and N_r redundant fragments (packet guard intervals). Depending on the type of the packet guard interval (ZP or CP), two schemes are proposed in [7].

3.1. Packet transmissions with Distributed ZP (D-ZP)

Here the packet guard time comprises N_r null fragments, where $N_0 + N_r N \geq L$. Each packet $\bar{\boldsymbol{u}}(n)$ has size $\bar{N} := (N_f + N_r)N$, and can be expressed as

$$\bar{\boldsymbol{u}}(n) = [\boldsymbol{u}^T(N_f n+1), \boldsymbol{u}^T(N_f n+2), \ldots, \boldsymbol{u}^T(N_f n+N_f), \underbrace{\mathbf{0}^T_{N\times 1}, \ldots, \mathbf{0}^T_{N\times 1}}_{N_r \text{ fragments}}]^T. \quad (4)$$

It should be noted that although we express a set of fragments as a packet, the transmitter simply sends fragments successively, without being necessary to form $\bar{\boldsymbol{u}}(n)$; i.e., no blocking delay or buffering is required at the transmitter.

The packet $\bar{\boldsymbol{u}}(n)$ can be expressed as

$$\bar{\boldsymbol{u}}(n) = \boldsymbol{T}\bar{\boldsymbol{s}}(n), \quad (5)$$

where $\bar{\boldsymbol{s}}^T(n) := [\boldsymbol{s}^T(N_f n+1), \ldots, \boldsymbol{s}^T(N_f n+N_f)]$ and

$$\boldsymbol{T} = \begin{bmatrix} \boldsymbol{I}_{N_f} \\ \mathbf{0}_{N_r\times N_f} \end{bmatrix} \otimes \boldsymbol{T}_{zp}, \quad (6)$$

with $\otimes$ denoting the Kronecker product.

At the receiver, we collect $N_f + N_r$ fragments in an $\bar{N} \times 1$ vector $\bar{\boldsymbol{x}}(n)$ that can be expressed as

$$\bar{\boldsymbol{x}}(n) = \bar{\boldsymbol{H}}_0\bar{\boldsymbol{u}}(n) + \bar{\boldsymbol{H}}_1\bar{\boldsymbol{u}}(n-1) + \bar{\boldsymbol{v}}(n), \quad (7)$$

where $\bar{\boldsymbol{H}}_0$ and $\bar{\boldsymbol{H}}_1$ are $\bar{N}\times\bar{N}$ square Toeplitz channel convolution matrices with first column $[h(0), \ldots, h(L), \mathbf{0}^T]^T$ first row $[h(0), \mathbf{0}^T]$, and with first row $[\mathbf{0}^T, h(L), \ldots, h(1)]$ last column $[h(1), \ldots, h(L), \mathbf{0}^T]^T$, respectively; and $\bar{\boldsymbol{v}}(n)$ is a zero-mean additive noise.

Since the last $N_0 + N_r N$ entries of $\bar{\boldsymbol{u}}(n)$ are zero, IBI caused by channels up to order $L_{\max} = N_0 + N_r N$ is removed. With the IBI removed, (7) reduces to a form similar to (3), but with the packet dimensionality $\bar{N}$ replacing the fragment size N such that

$$\bar{\boldsymbol{x}}(n) = \bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}}\bar{\boldsymbol{s}}(n) + \bar{\boldsymbol{v}}(n), \quad (8)$$

where

$$\bar{\boldsymbol{T}} = \boldsymbol{I}_{N_f} \otimes \boldsymbol{T}_{zp}, \quad (9)$$

and the channel mixing matrix $\bar{\boldsymbol{H}}_{tr}$ is a tall $\bar{N} \times N_f N$ Toeplitz matrix with first column $[h(0), h(1), \ldots, h(L), \mathbf{0}^T]^T$ and first row $[h(0), \mathbf{0}^T]$. Similar to $\boldsymbol{H}_{tr}$, the matrix $\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}}$ is found to be always full rank for any channel up to order $L_{\max} = N_0 + N_r N$, thanks to the $N_0 + N_r N$ padded zeros in $\bar{\boldsymbol{u}}(n)$. It thus follows readily that this D-ZP scheme inherits the symbol detectability and performance properties (maximum multipath diversity and coding gains) that have been established in [9, 12].

With regards to its bandwidth efficiency, $\mathcal{E}$, it suffices to observe that each $\bar{N}\times 1$ packet $\bar{\boldsymbol{u}}(n)$ in (4) contains $N_f M$ information-bearing symbols. Hence,

$$\mathcal{E} := \left(\frac{M}{M+N_0}\right)\left(\frac{N_f}{N_f+N_r}\right). \quad (10)$$

The first factor $M/(M+N_0)$ is the bandwidth efficiency without sending null fragments; i.e., the bandwidth efficiency of the original ZP fragment, while the second factor arises due to the transmission of the null fragments.

Now let us consider blind identifiability of D-ZP when there is no additive noise. For $N_d \geq N_f M$, we collect N_d received packets into $\boldsymbol{X}_{N_d}$ such that

$$\boldsymbol{X}_{N_d} = [\bar{\boldsymbol{x}}(1), \bar{\boldsymbol{x}}(2), \ldots, \bar{\boldsymbol{x}}(N_d)]. \quad (11)$$

If there is no additive noise, $\boldsymbol{X}_{N_d}$ is expressed as

$$\boldsymbol{X}_{N_d} = \bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}}\boldsymbol{S}_{N_d}, \quad (12)$$

where $\boldsymbol{S}_{N_d} = [\bar{\boldsymbol{s}}(1), \bar{\boldsymbol{s}}(2), \ldots, \bar{\boldsymbol{s}}(N_d)]$. For N_d sufficiently large, we can assume that $\boldsymbol{S}_{N_d}\boldsymbol{S}^{\mathcal{H}}_{N_d} > 0$, where $^{\mathcal{H}}$ denotes Hermitian transpose.

The rank of $\bar{N}\times N_f M$ matrix $\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}}$ is $N_f M$. Let the left null vectors of $\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}}$ be $\boldsymbol{u}_k := [u_k(1), \ldots, u_k(\bar{N})]^T$ for $k \in [1, \bar{N} - N_f M]$, i.e., $\boldsymbol{u}_k^{\mathcal{H}}\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}} = \mathbf{0}^T$ for $k \in [1, \bar{N} - N_f M]$, or equivalently,

$$\boldsymbol{U}^{\mathcal{H}}\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}} = \mathbf{0}, \quad (13)$$

where $\boldsymbol{U} := [\boldsymbol{u}_1, \boldsymbol{u}_2, \ldots, \boldsymbol{u}_{N_f M}]$.

For given $\boldsymbol{U}$ and $\bar{\boldsymbol{T}}$, we show in Appendix A that the non-trivial solution of (13) is unique within a scale factor. Thus, blind identification is possible by the so-called subspace method as follows: Vector multiplication with a Toeplitz matrix denotes convolution which is commutative. Since $\bar{\boldsymbol{T}}$ is real, $\boldsymbol{u}_k^{\mathcal{H}}\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}} = \mathbf{0}^T$ can be expressed as $\boldsymbol{h}^{\mathcal{H}}\boldsymbol{\mathcal{U}}_k\bar{\boldsymbol{T}} = \mathbf{0}^T$, where $\boldsymbol{h} := [h(0), \ldots, h(L)]^T$; $\boldsymbol{\mathcal{U}}_k$ is an $(L+1)\times N_f N$ Toeplitz matrix with first column $[u_k^*(1), \mathbf{0}^T]^T$ and first row $[\boldsymbol{u}_k^{\mathcal{H}}, \mathbf{0}^T]$. Stacking $\boldsymbol{h}^{\mathcal{H}}\boldsymbol{\mathcal{U}}_k\bar{\boldsymbol{T}} = \mathbf{0}^T$ for $k = 1, \ldots, \bar{N} - N_f M$, we obtain

$$\boldsymbol{h}^{\mathcal{H}}\left[\boldsymbol{\mathcal{U}}_1\bar{\boldsymbol{T}}, \boldsymbol{\mathcal{U}}_2\bar{\boldsymbol{T}}, \ldots, \boldsymbol{\mathcal{U}}_{\bar{N}-N_f M}\bar{\boldsymbol{T}}\right] = \mathbf{0}^T. \quad (14)$$

Since the non-trivial solution of (13) is unique within a scale factor, so is the non-trivial solution of (14) and hence blind identification is achieved by computing a non-trivial left null vector of $[\boldsymbol{\mathcal{U}}_1\bar{\boldsymbol{T}}, \ldots, \boldsymbol{\mathcal{U}}_{\bar{N}-N_f M}\bar{\boldsymbol{T}}]$, or equivalently, by a non-zero left null vector of

$$[\boldsymbol{\mathcal{U}}_1\bar{\boldsymbol{T}}, \ldots, \boldsymbol{\mathcal{U}}_{\bar{N}-N_f M}\bar{\boldsymbol{T}}][\boldsymbol{\mathcal{U}}_1\bar{\boldsymbol{T}}, \ldots, \boldsymbol{\mathcal{U}}_{\bar{N}-N_f M}\bar{\boldsymbol{T}}]^{\mathcal{H}} = \sum_{k=1}^{\bar{N}-N_f M} \boldsymbol{\mathcal{U}}_k\bar{\boldsymbol{T}}\bar{\boldsymbol{T}}^{\mathcal{H}}\boldsymbol{\mathcal{U}}_k^{\mathcal{H}}. \quad (15)$$

We summarize the above procedure:

1. *From received packets, construct $\boldsymbol{X}_{N_d}$ as in (11).*

2. *Compute the eigenvectors of $\boldsymbol{X}_{N_d}\boldsymbol{X}_{N_d}^{\mathcal{H}}$ corresponding to the $\bar{N} - N_f M$ smallest eigenvalues.*

3. *Set the eigenvector of* (15) *corresponding to the smallest eigenvalue to be the estimate of $\boldsymbol{h}$.*

We note that a scalar ambiguity inherent in blind estimation still remains.

Combining the results on symbol detectability in [7], we have established for D-ZP transmissions that:

Proposition 1 *If $N_0 + N_r N \geq L$, then D-ZP packet transmissions enable blind identification and guarantee symbol detectability (and thus full multipath diversity).*

We remark that the channel estimation procedure does not pose any restrictions on the FIR channel zeros provided that $N_0 + N_r N \geq L$, and it is robust even when the channel order is overestimated as in [9].

3.2. Packet Transmissions with Distributed CP

Instead of padding N_r null fragments as in the previous subsection, following the N_f ZP information bearing fragments, we pad in a circular fashion the first N_r (of the N_f) fragments. Specifically, the nth packet now has the form:

$$\tilde{\boldsymbol{u}}(n) = [\boldsymbol{u}^T(N_f n + 1), \ldots, \boldsymbol{u}^T(N_f n + N_f), \underbrace{\boldsymbol{u}^T(N_f n + 1), \ldots, \boldsymbol{u}^T(N_f n + N_r)}_{N_r \text{ fragments}}]^T. \quad (16)$$

Every N_f fragments in this scheme, that we naturally term D-CP, we simply re-transmit N_r of them. Different from D-ZP, and similar to the CP removal that takes place at an OFDM receiver, we remove the first $N_r N$ entries from each received packet. This operation removes IBI from (7), provided that we select N, N_r to satisfy: $N_r N \geq L$ [10].

As far as transmission rate, it is clear that D-CP has bandwidth efficiency identical to that of D-ZP. A nice feature of D-CP, not available in D-ZP, is that D-CP transmits fragments of the same structure. This in turn allows for easy adaptation of the transmitter to possible changes in N_f, N_r.

With regards to performance, thinking along uncoded OFDM lines, one would be tempted to infer that D-CP does not guarantee constellation and channel irrespective symbol detectability, and thus it does not enable the full multipath diversity. Interestingly, we establish in Appendix B that D-CP enjoys these nice features as well, provided that our fragment and packet parameters are chosen to satisfy:

$$N_f N_0 \geq L, \quad N_r N \geq L. \quad (17)$$

	packet size	bandwidth efficiency
D-ZP	63	2/3
D-CP	63	2/3
ZP (a)	27	2/3
ZP (b)	63	6/7

Table 1. Comparison of simulated systems

Proposition 2 *Under (17), D-CP guarantees constellation and channel irrespective blind identifiability as well as symbol detectability (and thus full multipath diversity) for any FIR channel up to order* $\min(N_f N_0, N_r N)$.

Comparing D-CP with D-ZP for the same (N_f, N_r), we observe that D-ZP guarantees blind identifiability and symbol detectability for slightly longer channel orders. In addition, D-CP is not as energy efficient as D-ZP, since we allocate $N_r/(N_f + N_r)$ percent of the transmit-power per packet to re-transmitting N_r fragments. This is the price we pay in D-CP for maintaining the fragment structure. The delay and complexity increase as (N_f, N_r) increase. The packet size (and thus bandwidth efficiency) depends not only on the maximum channel order L, but also on the channel coherence time. For D-CP to satisfy (17) for channels with relatively short coherence time, increasing N_0 and/or N_r also reduces the bandwidth efficiency.

4. NUMERICAL EXAMPLES

We generated 10^3 Rayleigh distributed channels of order $L = 9$, having complex zero-mean Gaussian taps with exponential power profile: $E\{|h(l)|^2\} = \exp(-l)$, for $l \in [0, L]$. The information symbols were drawn from a BPSK constellation.

We first considered D-ZP and D-CP transmissions with $(M, N_0) = (7, 2)$, which can accommodate symbol codewords of length $M = 7$, and can handle IBI for channels up to order 2. As our channels had order $L = 9$, the guard time in this case has insufficient length to remove the IBI. We thus selected $(N_f, N_r) = (6, 1)$, which imply bandwidth efficiency $(7/9)(6/7) = 2/3$, and a packet size of $(N_f + N_r)(M + N_0) = 7 \cdot 9 = 63$. We also tested two more ZP-based block transmissions that ensure channel-irrespective symbol-detectability for channels up to order 9:
(a) one having $(M, N_0) = (18, 9)$, packet size $M + N_0 = 27$, and bandwidth efficiency $M/(M + 9) = 2/3$, identical to those of D-ZP and D-CP transmissions;
(b) one having $(M, N_0) = (54, 9)$, and packet size $M + N_0 = 63$, which causes decoding delay equal to a packet in the D-ZP and D-CP transmissions, but enjoys higher bandwidth efficiency $54/63 = 6/7$.

Table 1 compares simulated systems in terms of: packet

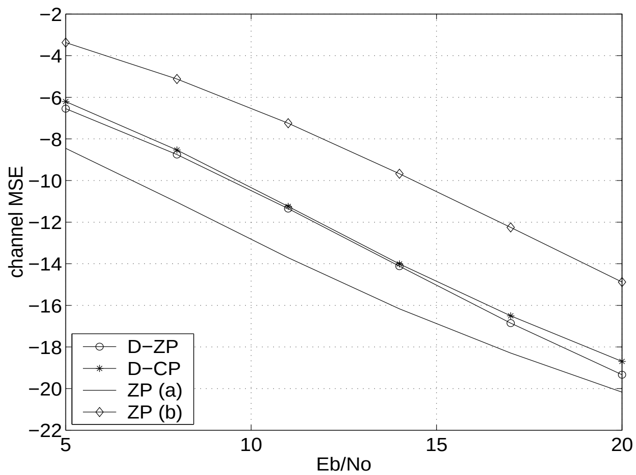

Fig. 3. channel MSE

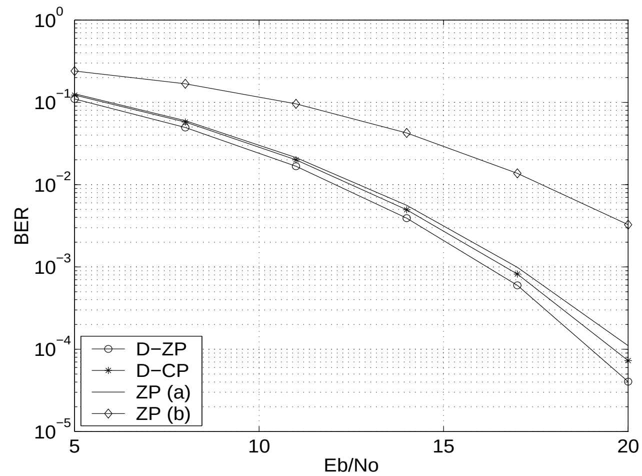

Fig. 4. BER performance

size and bandwidth efficiency. For blind identification of ZP (a) and (b), we adopted the algorithm proposed in [9]. For each realized channel, we utilized 180 packets for D-ZP, D-CP and ZP (b); and 420 packets for ZP (a) so that they have the identical observation time.

As a performance measure of channel estimation quality, we computed the (normalized) channel mean squared error (MSE) defined as

$$\frac{1}{N_t}\sum_{i=1}^{N_t}\min_{c_i}\frac{||\boldsymbol{h}-c_i\hat{\boldsymbol{h}}_i||^2}{||\boldsymbol{h}||^2},$$

where N_t is the number of trials; $\hat{\boldsymbol{h}}_i$ is the ith estimate in the Monte-Carlo experiments; and c_i is to remove the constant ambiguity, which is also utilized to construct zero-forcing (ZF) equalizers for symbol detection.

Fig. 3 depicts channel MSE as a function of E_b/N_0. Among all schemes, ZP (a) having minimum packet size exhibits the best performance. D-ZP and D-CP have similar performance, while ZP (b) of the same packet size with D-ZP and D-CP blindly estimate channels worst. All blind algorithms are based on the orthogonality between the range space of a channel matrix and the space spanned by white noises, i.e., so-called noise subspace. The rate of the dimension of noise subspace to the whole space is given by one minus bandwidth efficiency. ZP (b) has the best bandwidth efficiency, while it only exploits smaller noise space. Fig. 3 clearly suggests that there exists a trade-off between bandwidth efficiency and blind channel identification performance.

Fig. 4 illustrates BER of ZF equalizers constructed from estimated channels. For simplicity, we removed the scaler (phase) ambiguity inherited in any blind identification and equalization schemes. We remark that in practice, since phase can not be blindly estimated, differential PSK should be employed, which will leads to performance loss at most 3dB compared to phase coherent detection, see e.g., [8].

Clearly, the D-ZP and D-CP schemes exhibit better performance than ZP (b) at the expense of rate reduction. It is interesting to note that although they have worse channel estimates than ZP (a), they slightly outperform ZP (a) that has identical bandwidth efficiency. We believe that the reason behind this improvement, is the fact that D-ZP transmissions offer a better conditioned channel matrix than ZP (a), and this leads to a larger coding gain (recall that they both enable the maximum multipath diversity gain since they both guarantee symbol detectability [11]).

Theoretical analysis on the performance differences and further comparisons with channel coded transmissions will be reported in the future.

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A. PROOF OF THE UNIQUENESS OF SOLUTION OF (13)

Let the solution of $\boldsymbol{U}^{\mathcal{H}}\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}} = \mathbf{0}$ be $\boldsymbol{h} = [h(0), h(0), \ldots, h(L)]^T$. Suppose for simplicity that zeros, denoted by $\{v_l\}_{l\in[1,L]}$, of the channel transfer function $H(z) := \sum_{l=0}^{L} h(l)z^{-l}$ are different. Since $\bar{\boldsymbol{H}}_{tr}$ is a column-wise Toeplitz matrix, its left null space $\mathcal{N}(\bar{\boldsymbol{H}}_{tr}^{\mathcal{H}})$ is spanned by the Vandermonde vectors associated with the zeros $\{v_l\}_{l\in[1,L]}$ of the channel transfer function.

Let $\boldsymbol{v}_{m,\bar{N}} := [1, v_m, \ldots, v_m^{\bar{N}-1}]^T$ be the Vandermonde vectors of size $\bar{N}$ and construct

$$\boldsymbol{V}_{\bar{N}} = [\boldsymbol{v}_{1,\bar{N}}, \boldsymbol{v}_{2,\bar{N}}, \ldots, \boldsymbol{v}_{L,\bar{N}}]$$

From $\mathcal{N}(\bar{\boldsymbol{H}}_{tr}^{\mathcal{H}}) \subseteq \mathcal{N}((\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}})^{\mathcal{H}})$, it must be $\boldsymbol{V}^{\mathcal{H}}\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}} = \mathbf{0}$. We will prove that $\boldsymbol{V}_{\bar{N}}^{\mathcal{H}}\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}} = \mathbf{0}$, and hence $\boldsymbol{U}^{\mathcal{H}}\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}} = \mathbf{0}$, has a unique non-zero solution.

Suppose another channel $\boldsymbol{h}' = [h'(0), h'(1), \ldots, h'(L)]^T$ such that hence $\boldsymbol{h}' \neq c\boldsymbol{h}$ for a non-zero constant c, and construct its associated Toeplitz channel matrix $\bar{\boldsymbol{H}}'_{tr}$. Since $\bar{\boldsymbol{H}}'_{tr}$ is a column-wise Toeplitz matrix, $\boldsymbol{V}_{\bar{N}}^{\mathcal{H}}\bar{\boldsymbol{H}}'_{tr}\bar{\boldsymbol{T}} = \boldsymbol{D}_{H'}\boldsymbol{V}_{N_fN}^{\mathcal{H}}\bar{\boldsymbol{T}}$, where $\boldsymbol{D}_H$ is an $L \times L$ diagonal matrix defined as

$$\boldsymbol{D}_{H'} := \mathrm{diag}[H'(v_1), H'(v_2), \ldots, H'(v_L)],$$

with $H'(z) := \sum_{l=0}^{L} h'(l)z^{-l}$.

For $H'(z) \neq cH(z)$, at least one diagonal element, namely the kth element, of $\boldsymbol{D}_H$ is non-zero. On the other hand, it is easy to see that the kth row of $\boldsymbol{V}_{N_fN}^{\mathcal{H}}\bar{\boldsymbol{T}}$, i.e., $\boldsymbol{v}_{k,N_fN}^{\mathcal{H}}\bar{\boldsymbol{T}}$, is a non-zero vector. This implies that if $H'(z) \neq cH(z)$, then $\boldsymbol{V}_{\bar{N}}^{\mathcal{H}}\bar{\boldsymbol{H}}'_{tr}\bar{\boldsymbol{T}} \neq \mathbf{0}$, which proves the uniqueness of the solution of $\boldsymbol{V}_{\bar{N}}^{\mathcal{H}}\bar{\boldsymbol{H}}_{tr}\bar{\boldsymbol{T}} = \mathbf{0}$.

B. PROOF OF PROPOSITION 2

The D-CP packet $\tilde{\boldsymbol{u}}(n)$ can be expressed from (16) as $\tilde{\boldsymbol{u}}(n) = \tilde{\boldsymbol{T}}\bar{\boldsymbol{s}}(n)$, where

$$\tilde{\boldsymbol{T}} = \begin{bmatrix} & \boldsymbol{I}_{N_f} \\ \boldsymbol{I}_{N_r} & \mathbf{0} \end{bmatrix} \otimes \boldsymbol{T}_{zp}. \qquad (18)$$

Let $\boldsymbol{F}$ be the $N_fN \times N_fN$ FFT matrix with (m,n)th entry $[\boldsymbol{F}]_{m,n} = (N_fN)^{-\frac{1}{2}}W^{-mn}$, where $W := \exp[j2\pi/(N_fN)]$, and let $\boldsymbol{f}_j$ be the jth column of $\boldsymbol{F}$. Also define $\boldsymbol{F}_{i:j}$ as the submatrix of $\boldsymbol{F}$, that is formed starting with the ith column and ending with the jth column of $\boldsymbol{F}$. It then follows that $\tilde{\boldsymbol{T}}$ can be expressed as $\tilde{\boldsymbol{T}} = \tilde{\boldsymbol{V}}\tilde{\boldsymbol{F}}$, where $\tilde{\boldsymbol{V}}$ is an $\bar{N} \times N_fN$ Vandermonde matrix given by $\tilde{\boldsymbol{V}}^{\mathcal{H}} = [\boldsymbol{f}_1, \boldsymbol{f}_2, \ldots, \boldsymbol{f}_{N_fN}, \boldsymbol{f}_1, \ldots, \boldsymbol{f}_{N_rN}]$, and $\tilde{\boldsymbol{F}}$ is a matrix defined as

$$\tilde{\boldsymbol{F}} = [\boldsymbol{F}_{1:M}, \boldsymbol{F}_{1+N:M+N}, \ldots, \boldsymbol{F}_{1+(N_f-1)N:M+(N_f-1)N}].$$

Since $\tilde{\boldsymbol{F}}$ is an $N_fN \times N_fM$ submatrix of $\boldsymbol{F}$, any N_fM rows of $\tilde{\boldsymbol{F}}$ are linearly independent. It then follows from [6, Thms. 2,3] that under (17), $\tilde{\boldsymbol{T}}$ attains symbol detectability as well as blind identifiability.