AN INTEGRATED SIGNAL PROCESSING FRAMEWORK FOR MULTIUSER CDMA COMMUNICATIONS

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ABSTRACT

The major signal processing challenges in wireless CDMA systems stem from time-varying multipath propagation effects, multiaccess interference (MAI), and the complexity of the DSP algorithms. We propose a framework based on canonical multipath-Doppler coordinates for addressing these issues in an integrated fashion. The canonical coordinates are derived from a fundamental characterization of channel propagation dynamics in terms of discrete multipath-delayed and Doppler-shifted copies of the transmitted waveform. These delayed and Doppler-shifted spreading waveforms constitute a natural fixed basis and dictate a canonical low-dimensional processing. In addition to providing a robust vehicle for channel modeling and estimation, the framework facilitates exploitation of dispersion effects for MAI suppression via subspace-based processing in the canonical coordinates. Finally, the low-dimensional subspace formulation affords a direct handle on the complexity of the DSP algorithms.

1. INTRODUCTION

Code division multiple access (CDMA) has emerged as one of the most promising technologies for meeting the challenges of the physical network layer, as evident from its prominence in the wireless infrastructure envisioned for the third and future generation systems. Innovative DSP techniques are playing a progressively important role in the design of CDMA systems due to the high complexity of processing required in the physical layer. The major DSP challenges in CDMA system design stem from three key factors that have a significant impact on performance:

Channel propagation dynamics manifested as multipath dispersion, multipath fading, and temporal variations or Doppler effects.

Multiaccess interference due to multiple simultaneous users, which is further accentuated by multipath propagation effects.

Complexity of the DSP algorithms.

Even though the above factors are clearly interrelated, existing techniques reflect a piecemeal approach due to the lack of a framework connecting the various physical layer facets. In contrast, the progressively stringent performance demands imposed by future wireless systems dictate an integrated approach to deliver fully optimized systems.

In this paper, we propose DSP in *canonical multipath-Doppler coordinates* as an integrated framework for combating time-varying multipath distortion, suppressing multiaccess interference, and managing the complexity of the resulting algorithms. The canonical coordinates are derived from a fundamental characterization of the channel propagation dynamics in terms of discrete multipath-delayed and Doppler-shifted copies of the *transmitted* spread-spectrum waveform which constitute a *fixed* canonical basis for representing the received signal [1]. A well-known advantage of CDMA, by virtue of spread-spectrum signaling, is its remarkable ability to combat fading by *exploiting* multipath propagation effects [2]. Our framework promises a new DSP innovation: further exploiting the time-varying multipath effects to suppress multiaccess interference via subspace-based processing in the canonical coordinates.

The next section introduces the generic receiver structure in the canonical coordinates. Section 2 describes the fundamental channel characterization that underlies the proposed framework. Sections 4 and 5 discuss channel modeling and interference suppression issues in receiver design.

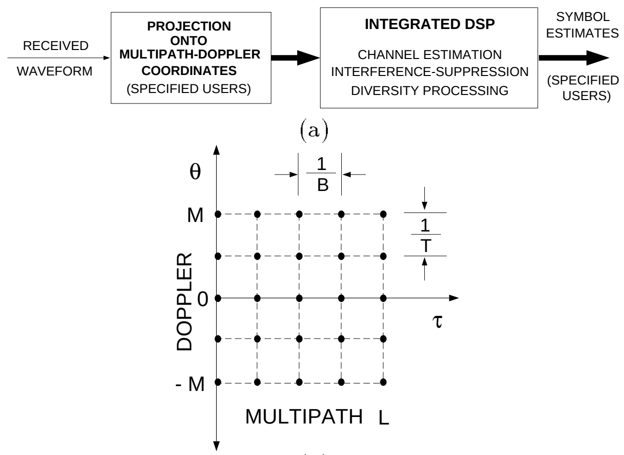
2. CANONICAL FRAMEWORK

Figure 1 describes *DSP in canonical multipath-Doppler coordinates* that is at the heart of our framework. The front-end processing corresponds to projecting the received waveform onto the canonical coordinates. Each user corresponds to unique coordinates defined by its spreading code, which are computed for each received *symbol*. Canonical coordinates, taken together for all users and symbols of interest, constitute sufficient statistics for demodulation—*all DSP can be performed in the canonical coordinates.*

The coordinates for each symbol of a particular user are computed by correlating the received signal with time- and frequency-shifted copies of the user spreading waveform

$$z_{ml} = \int r(t) q^* \left(t - \tau_o - \frac{l}{B} \right) e^{-j\frac{2\pi m t}{T}} dt, \quad (1)$$
$$l = 0, \cdots, L \quad ; \quad m = -M, \cdots, 0, \cdots, M,$$

where $r(t)$ denotes the received waveform, τ_o denotes the user delay, and $q(t)$ is the user spreading waveform of duration T and bandwidth B. In effect, the canonical multipath-Doppler coordinates define an $(L+1)(2M+1)$-dimensional subspace for representing the channel distorted signal of



(b)

Figure 1: DSP at the receiver in canonical multipath-Doppler coordinates. (a) Overall receiver schematic. (b) The uniformly spaced canonical coordinate grid.

each user. The subspace is spanned by the *fixed* basis

$$q_{ml}(t) = q(t - l/B)e^{j\frac{2\pi mt}{T}}, \tag{2}$$

determined by the user's spreading waveform $q(t)$ [1]. We note that under certain conditions $\{q_{ml}(t)\}$ constitute an approximately orthogonal basis [1].

As illustrated in Figure 1(b), the indices l and m correspond to a uniform sampling of multipath delays τ ($\Delta\tau = 1/B$) and Doppler shifts θ ($\Delta\theta = 1/T$), respectively, that are encountered during propagation. The front-end projection onto the canonical coordinates can be performed efficiently via a time-frequency generalization of the RAKE receiver — a bank of RAKE receivers matched to different canonical Doppler frequencies [1].

In addition to providing an equivalent, robust characterization of virtually all existing channel modeling approaches, canonical multipath-Doppler coordinates connect the channel propagation and multiaccess interference effects in a very natural and intuitive fashion which leads to new insights and methodologies. First of all, by their very nature, processing relating to channel propagation can be directly performed in the canonical coordinates [1]. Moreover, the same coordinates provide a natural subspace-based representation of the desired signal and multiaccess interference which fully incorporates channel distortion effects and leads to new techniques for interference suppression. Finally, the *parsimonious* nature of the canonical coordinates affords a direct handle on DSP complexity.

3. CANONICAL SIGNAL REPRESENTATION

In this section, we describe a fundamental characterization of channel propagation effects that underlies canonical multipath-Doppler coordinates [1]. Propagation effects can be generally modeled as a linear time-varying system [2] and are best illustrated by focusing on transmission of a single symbol waveform $q(t)$ in a single-user system:

$$r(t) = s(t) + n(t) \tag{3}$$

$$s(t) = \int_0^{T_m}\int_{-B_d}^{B_d} H(\theta,\tau)q(t-\tau)e^{j2\pi\theta t}d\theta d\tau, \tag{4}$$

$0 < t \leq T$, where $r(t)$ is the received noisy waveform consisting of the information bearing signal $s(t)$ and additive white Gaussian noise (AWGN) $n(t)$. Channel propagation is characterized by the multipath-Doppler *spreading function* $H(\theta,\tau)$ which depicts the temporal and spectral dispersion produced by the channel.[1] The variable τ corresponds to multipath propagation delays with T_m denoting the *multipath spread* of the channel. Doppler shifts are denoted by θ, with B_d denoting the *Doppler spread* of the channel.

The notion of canonical coordinates is based on the following basic idea: due to the inherently finite duration T and essentially finite bandwidth B of the transmitted waveform, the receiver "sees" only *finitely many* degrees of freedom in the signal [1]. These essential degrees of freedom are captured by the canonical multipath-Doppler coordinates as dictated by the following fundamental characterization [1]

$$s(t) \approx \frac{1}{TB}\sum_{l=0}^{L}\sum_{m=-M}^{M}\widehat{H}\left(\frac{m}{T},\frac{l}{B}\right)q\left(t-\frac{l}{B}\right)e^{j\frac{2\pi mt}{T}} \tag{5}$$

which leads to the canonical basis (2) corresponding to the uniform grid in Figure 1(b). The coefficients in the basis expansion are samples of the smoothed spreading function

$$\widehat{H}(\theta,\tau) = TB\int_0^{T_m}\int_{-B_d}^{B_d} H(\theta',\tau') \mathrm{sinc}((\theta-\theta')T)\mathrm{sinc}((\tau-\tau')B)d\theta' d\tau' \tag{6}$$

that arises due to the time limited and essentially band limited nature of $q(t)$ [1]. The approximation in (5) can be made arbitrarily precise by increasing the number of summation terms — in practice, only a few dominant terms capture virtually all the signal energy. The number L of dominant multipath coordinates is equal to the multipath spread normalized by the temporal signaling resolution ($1/B$): $L = \lceil T_m B \rceil$. Similarly, the number of dominant Doppler coordinates is equal to the Doppler spread normalized by the frequency resolution ($1/T$): $M = \lceil TB_d \rceil$.

We note that the definition of the effective bandwidth B affects the structure of the basis (2) and the accuracy of (5). In particular, for direct sequence spread-spectrum waveforms, B is inversely related to the chip duration $T_c = T/N$, where N is the spreading gain. The choice $B \approx 1/T_c$ yields an approximately orthogonal basis (2) at the expense of some loss of accuracy in (5). The accuracy of the representation (2) can be improved via the choice $B \approx \mathcal{O}/T_c$, $\mathcal{O} \geq 2$ (oversampling by a factor of $\mathcal{O}$, typically 2 or 4), albeit at the cost of losing orthogonality of the basis (2).

[1] We note that T may be significantly longer than the *inter-symbol* duration in order to exploit channel diversity, thereby making Doppler effects significant over the symbol duration [1].

4. CHANNEL MODELING AND ESTIMATION IN CANONICAL COORDINATES

The characterization (5) asserts that all information about the channel propagation dynamics that is observable at the receiver is captured by the canonical coefficients $\widehat{H}_{ml} = \widehat{H}(m/T, l/B)$ on the uniform grid in Figure 1(b). The reason is that due to the essentially finite time-bandwidth product of the transmitted waveform $q(t)$, the received signal $s(t) = \alpha q(t-\tau)e^{j2\pi\theta t}$ corresponding to arbitrary (θ, τ) coordinates admits an effective representation with respect to the canonical basis (2). Figure 2 illustrates several important examples of existing channel models that are captured by modeling in canonical coordinates. In contrast to modeling via a *fixed* basis in the canonical coordinates, most existing models require knowledge of the true multipath delays and Doppler shifts which leads to *data-dependent* underlying basis waveforms and hence increased complexity.

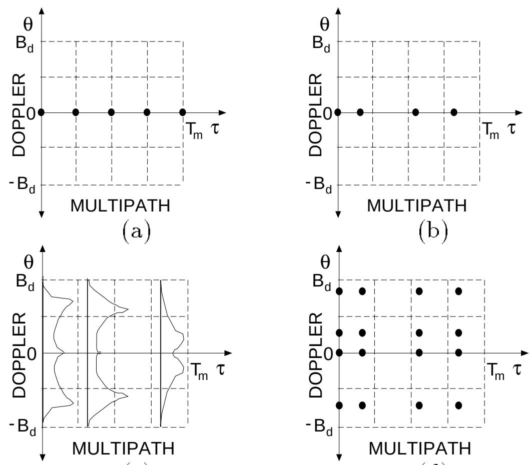


Figure 2: Illustration of various channel models captured by the canonical coordinates via (5). (a) The tapped delay-line multipath model used by the RAKE receiver [2]. (b) Modeling of arbitrary multipath delays. (c) Time-varying extension of (b) via autoregressive modeling of the Doppler spectrum [3]. (d) Time-varying extension of (b) via arbitrary discrete Doppler shifts [4].

Figure 3 demonstrates that a matched filter (MF) receiver in the canonical coordinates can deliver near-optimal performance at significantly lower complexity compared to the ideal receiver that requires knowledge of all the multipath delays. The comparison is made for a single-user coherent system with $N = 31$ spreading gain and employing a noise-free pilot transmission for channel estimation. A slow fading environment is modeled by $L_T = 64$ uniformly spaced independent multipath components, spread over $T_m = 2T_c$ and all of equal power. The canonical RAKE receiver corresponds to Figure 2(a) and takes the form

$$\hat{b} = \text{sign}\left\{\text{real}\left(\sum_{l=0}^{L} \widehat{H}_l^* z_l\right)\right\} \tag{7}$$

corresponding to the $L = \lceil T_m/B \rceil = T_m\mathcal{O}/T_c = 2\mathcal{O}$ canonical basis waveforms $\{q(t - lT_c/\mathcal{O})\}$, where $\mathcal{O}$ denotes the oversampling factor. The ideal receiver corresponds to Figure 2(c) and is matched to all the L_T multipaths

$$\hat{b} = \text{sign}\left\{\text{real}\left(\sum_{l=0}^{L_T} H^*(\tau_l)\int r(t)q^*(t-\tau_l)dt\right)\right\}. \tag{8}$$

Note that the performance of the canonical receiver for $\mathcal{O} =$

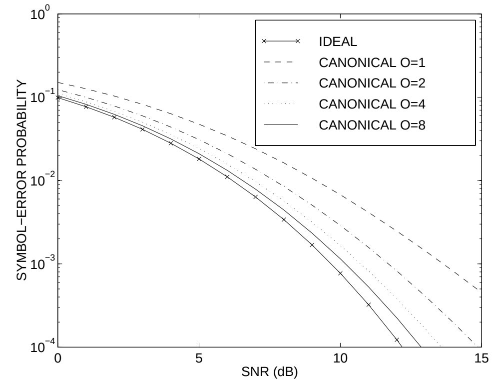


Figure 3: Performance of matched filtering in the ideal (physical) versus canonical coordinates.

4 or 8 is within 1dB of ideal performance. Furthermore, the complexity of the canonical receiver is substantially lower than that of the ideal receiver. As opposed to $L+1$ (at most 17 in Figure 3) MFs in the canonical receiver, the ideal receiver requires L_T (64 in this case) MFs. Furthermore, after synchronization, the canonical receiver only requires estimates of $L+1$ coefficients $\widehat{H}_l$, whereas the ideal receiver requires estimation of L_T delays τ_l and $H(\tau_l)$. As noted earlier, most existing receivers adopt the "ideal" design, as depicted in Figure 2(b), for dominant scatterers.

We note that stochastic modeling of $H(\theta, \tau)$ can also be efficiently accomplished by imposing an appropriate statistical model on the (few) coefficients $\widehat{H}_{ml}$. Statistical modeling is appropriate for capturing the phenomenon of fading, such as the wide-sense stationary uncorrelated scattering (WSSUS) model [2]. The WSSUS channel affords intrinsic diversity to combat fading that can be exploited via spread-spectrum signaling. Canonical coordinates fully capture the inherent channel diversity — each coordinate corresponds to a diversity channel — that is achieved via the canonical time-frequency RAKE receiver [1]. The channel in Figure 3 affords roughly 4 level diversity that is efficiently captured by the 4-8 MFs in the canonical receiver.

5. INTERFERENCE SUPPRESSION IN CANONICAL COORDINATES

Multiaccess interference (MAI) is intimately affected by channel dispersion effects and canonical coordinates provide provide a natural platform for efficiently incorporating channel propagation effects into MAI suppression. In a multiuser system, the k-th user is associated with a $(L_k+1)(2M_k+1)$-dimensional subspace corresponding to its unique canonical coordinates defined via (5) and (2) in terms of its spreading waveform $q_k(t)$. This formulation provides a new subspace-based approach for suppressing MAI by exploiting the additional degrees of freedom afforded by channel dispersion effects.

The basic idea is illustrated in Figure 4 depicting the special case of coherent linear processing for demodulating the desired user. The top branch in Figure 4 corresponds

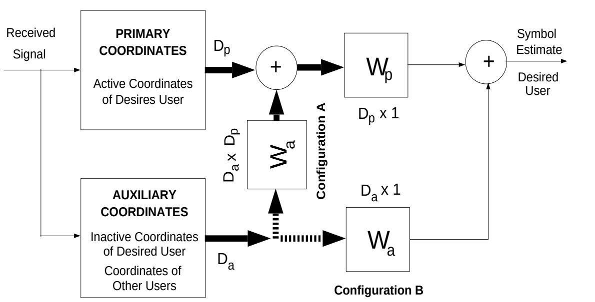


Figure 4: Generic linear receiver structure.

to the single-user receiver, denoted by $\mathbf{w}_p$, which combines the *primary* coordinates — the $D_p = (L+1)(2M+1)$ *active* multipath-Doppler coordinates — carrying signal energy of the desired user. The maximal-ratio-combiner (MRC) which exploits multipath-Doppler diversity [1] but ignores MAI is given by $\mathbf{w}_p = \mathbf{h} = [\widehat{H}_{ml}]$, where $[\widehat{H}_{ml}]$ denotes an $(L+1)(2M+1)$-dimension vector formed from $\widehat{H}_{ml}$. However, by virtue of the subspace structure, even the single-user receiver possesses MAI suppression capability through design of $\mathbf{w}_p$. For example, given the knowledge of the channel coefficients $\mathbf{h}$, the MMSE solution for demodulating the desired user is given by $\mathbf{w}_p^{mmse} = \mathbf{R}_{\mathbf{z}}^{-1}\mathbf{h}$ where $\mathbf{z} = [z_{ml}]$ (see (1)) and $\mathbf{R}_z = \mathrm{E}[\mathbf{z}\mathbf{z}^H]$. Note that this MMSE receiver

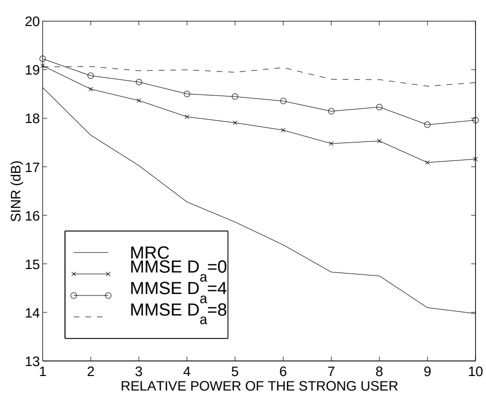


Figure 5: MAI suppression in canonical coordinates with increasing number D_a of auxiliary coordinates.

operates in the primary coordinates of the desired user (top branch in Figure 4) and provides minimal complexity MAI suppression while maximally exploiting channel diversity. In particular, the complexity is significantly lower compared to the chip-rate MMSE receivers proposed in [5].

The *auxiliary* coordinates in the lower branch in Figure 4 provide D_a additional degrees of freedom for adequate MAI suppression that may be required, depending on the number of strong interfering users. There are two natural mechanisms for systematically introducing auxiliary coordinates. On one hand, centralized receivers may be approached by progressively including canonical coordinates corresponding to *other* users. On the other hand, decentralized receivers may be approached by adding the *inactive* canonical coordinates of the desired user (outside the $(L+1)(2M+1)$-dimensional *active* square in Figure 1(b)). In between the two extremes is a whole range of *hybrid* receivers that attain desired auxiliary degrees of freedom by combining decentralized and centralized coordinates. Another dimension for flexibility comes from the various ways in which the primary and auxiliary coordinates are *combined*, as depicted by Configurations A and B in Figure 4. Configuration A corresponds to MAI suppression, via $\mathbf{w}_a$, followed by diversity combining/MAI suppression through $\mathbf{w}_p$. Configuration B corresponds to *joint* diversity combining and MAI suppression through choice of $\mathbf{w}_a$ and $\mathbf{w}_p$.

Figure 5 depicts the signal-to-interference-and-noise ratio (SINR) of a decentralized MMSE receiver for different auxiliary multipath dimensions D_a as a function of the relative (to desired user) interference power.[2] It is based on a slow fading environment ($T_m = 4T_c$; $N = 64$) with 4 users, one of which is a strong interferer. It illustrates that even minimal complexity MAI suppression in the primary coordinates can yield significant gains when there are a few strong interferers.

6. CONCLUSION

The proposed framework for receiver design in canonical multipath-Doppler coordinates provides a natural platform for dealing with channel propagation effects, MAI, and the complexity of the resulting DSP algorithms, all in an integrated fashion. From a channel propagation perspective, the canonical coordinates obviate the need for estimating arbitrary delays and Doppler shifts, thereby substantially reducing receiver complexity. In the context of MAI, the canonical subspace structure provides a systematic approach for designing minimal complexity receivers that in fact exploit dispersion effects for MAI suppression.

7. REFERENCES

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