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Letter

Transmission Systems

Narrowband PPM semi-'blind' spatial-rake receiver & co-channel interference suppression[†]

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SUMMARY

Among the open-literature on pulse-position-modulation (PPM) radiowave wireless communications, this work is first to advance a semi-'blind'/'blind' spatial-rake receiver with interference-rejection capability. This proposed adaptive 'smart antennas' detector uses the signal-of-interest's (SOI) earlier decoded information-symbols to segment earlier collected data into two data-groups: one data-group with the SOI and co-channel-interference and noise, with the other data-group containing only the latter two. These two data-groups' spatial-correlation matrices' generalised-eigenvector maximises the 'blind' spatial beamformer's output signal-to-interference-and-noise ratio (SINR) with*out* prior knowledge of (1) the multi-access user interferers' (MAUI) arrival directions, delays nor powers, (2) the signal-of-interest's (SOI) spatial signature at the receiving sensor-array[‡], and (3) the mobile's receiving-antennas' nominal/actual array-geometry and gain/phase responses. This proposed scheme is semi-'blind' because it needs a pilot sequence from the SOI. Copyright © 2006 AEIT.

1. LITERATURE REVIEW ON PPM RADIOWAVE 'SMART ANTENNAS' RECEIVERS

Pulse position modulation (PPM) is common for wired or wireless communication in fibre-optic communications and wireless-optic communications, and PPM is occasionally used for wireless infrared communications. A sensor-array's effective beam-pattern response to a PPM-like wireless signal has been studied in References [1–4]. Radiowave PPM *temporal* rake-receivers have appeared in the literature (e.g. Reference [5]), but not *spatial*-rake receivers. Non-adaptive sum-and-delay beam techniques are available for PPM in the defence-technology literature (e.g. Reference [6]), but these cannot handle co-channel interference. Radiowave PPM antenna-selection has been investigated in References [7, 8]. Unavailable in the open literature (prior to this paper's conference edition [9]) is any PPM radiowave antenna-array receiver capable of blind spatial beaming to constructively sum the signal-of-interest (SOI) and to suppress co-channel interference. The present paper proposes the open-literature's first such 'blind' spatial-rake receiver for radiowave PPM signals with bandwidths significantly smaller than the inverse of the time the signal takes to travel

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[†] Part of this paper was presented at the IEEE Annual Canadian Conference on Electrical & Computer Engineering, Saskatoon, Saskatchewan, Canada, May 1–4, 2005 [9].

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[‡] This means that the fading may be, but needs not be, statistically uncorrelated across the antennas in the mobile receiver.

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across the spatial aperture 'smart antennas' receiver[§]—all with *no* prior knowledge of any incident sources' incident angle or of the receiver's antenna-array's array manifold. The present algorithm achieves 'blind' space-frequency co-channel interference suppression by attempting to form two parallel sets of data—the first set (hereafter labelled as 'S + I + N') contains the desired signal plus the co-channel interference and noise; the second set (hereafter labelled as 'I + N') contains only the interference and noise. These two data sets will be processed to form a beam over the spatial direction-of-arrival coordinates to null co-channel interferers while preserving the SOI. An analogous beamforming technique has previously been applied to TDMA [10], FH-CDMA [11] and DS-CDMA [12, 13] signalling.

2. THE COLLECTED DATA'S STATISTICAL MODEL

The kth unit-power pulse-position modulated signal may be expressed as[‖]:

$$s_k(t) = \sum_{i=1,2,\ldots} u(t - iT_b - m_{k,i}T_p) \qquad (1)$$

where T_b symbolises the information-symbol period, $T_p = T_b/M$ denotes the pulse period, $m_{k,i} \in \{0, \ldots, M-1\}$ stands for the value of the ith M-ary information-symbol of the kth source, $u(t)$ denotes the pulse shape and (for mathematical simplicity) equals to 1 for $0 \leq t < T_p$ and 0 elsewhere. It is further required that the (SOI, indexed at $k = 1$ without loss of generality) and the strongest co-channel interferers persist for at least $I + 1$ information-symbol periods.

The L antennas (which may have unknown or uncalibrated[¶] spatial geometry and/or gain-phase-polarisational response) collect the $L \times 1$ baseband-equivalent data at time t,

$$\mathbf{z}(t) = \sum_{k=1}^{K} \sqrt{\mathcal{P}_k}\mathbf{a}_k s_k(t - \tau_k) + \mathbf{n}(t) \qquad (2)$$

where K denotes the number of incident PPM narrowband sources, $\mathcal{P}_k$ corresponds to the kth source's power, $\mathbf{a}_k$ refers to the kth source's $L \times 1$ steering-vector[**] *a priori un*known to the receiver, and τ_k symbolises the kth source's relative propagation delay (with the SOI's $\tau_1 = 0$ without loss of generality). All K signals are assumed to be narrowband in that each signal's bandwidth is much smaller than the inverse of the time taken for that signal to travel along the antenna-array's geometric aperture. If the SOI's propagation-channel is frequency-selective, the non-dominant paths would be regarded as interference in (T_2).

With no loss of generality, let the SOI has $k = 1$. The present problem is to estimate $m_{1,I+1}$, given $\{\mathbf{z}(nT_s), 0 \leq n < IT_b/T_s\}$, where T_s refers to the time-sampling period with T_p/T_s being an integer. Estimates $\{\hat{m}_{1,i}, i = 0, \ldots, I-1\}$ of the preceding I information-symbols are used in decision feedback but need not be perfectly correct.

3. A PPM 'BLIND' SPATIAL-RAKE RECEIVER TO REJECT COCHANNEL INTERFERENCE

The present algorithm collects two parallel groups of data at the $(I+1)$th information-symbol period, based on the SOI's I number of earlier decoded information-symbols. See Figure 1. The first set (hereafter labelled 'S + I + N') contains the SOI plus the co-channel PPM interference and additive noise. The second set (hereafter labelled 'I + N') contains only interference and noise. The 'S + I + N' data-group equals $\{\mathbf{z}(nT_s), \forall n, \forall i \in \{0, \ldots, I-1\} | 0 \leq nT_s + \tau_k - iT_b - m_{1,i}T_p < T_p\}$; and the 'I + N' data-group equals all remaining collected time-samples. By the above definition, the interference and noise in the 'I + N' data-group would differ from those in the 'S + I + N' data-group at any one time-instance. However, if the co-channel interference persists for at least $I + 1$ information-symbols, the 'overall' temporal behaviour of the co-channel interference and noise in the 'I + N' data-group approximates that in the 'S + I + N' data-group. Based on these two data-groups, adaptive beamforming weights may be 'blindly' computed to constructively sum the SOI in the L

[§] This condition allows the incident signal's relative arrival delays at various receiving antennas to be approximated as complex-phases. Ultrawideband signals violate this condition.

[‖] Though this signal model assumes no time-hopping (TH), the proposed algorithm may be readily modified for TH-PPM.

[¶] It would be impractical to continually calibrate a transceiver's antennas. An antenna's gain/phase/polarisation response drifts with time; and it suffers complex mutual coupling not only with other antennas in the mobile transceiver, but also with any passing electromagnetic reflector or the human body. Continual calibration of the antenna array can partly (but only partly) alleviate this problem, but is very expensive in terms of the architectural complexity required of the communication system and in terms of the mobile receiver's down time. The mobile receiver's antennas are typically uncalibrated, perhaps with unknown nominal gain/phase/polarisation responses.

[**] The source needs not be spatially coherent across the antenna-array's geometric aperture.

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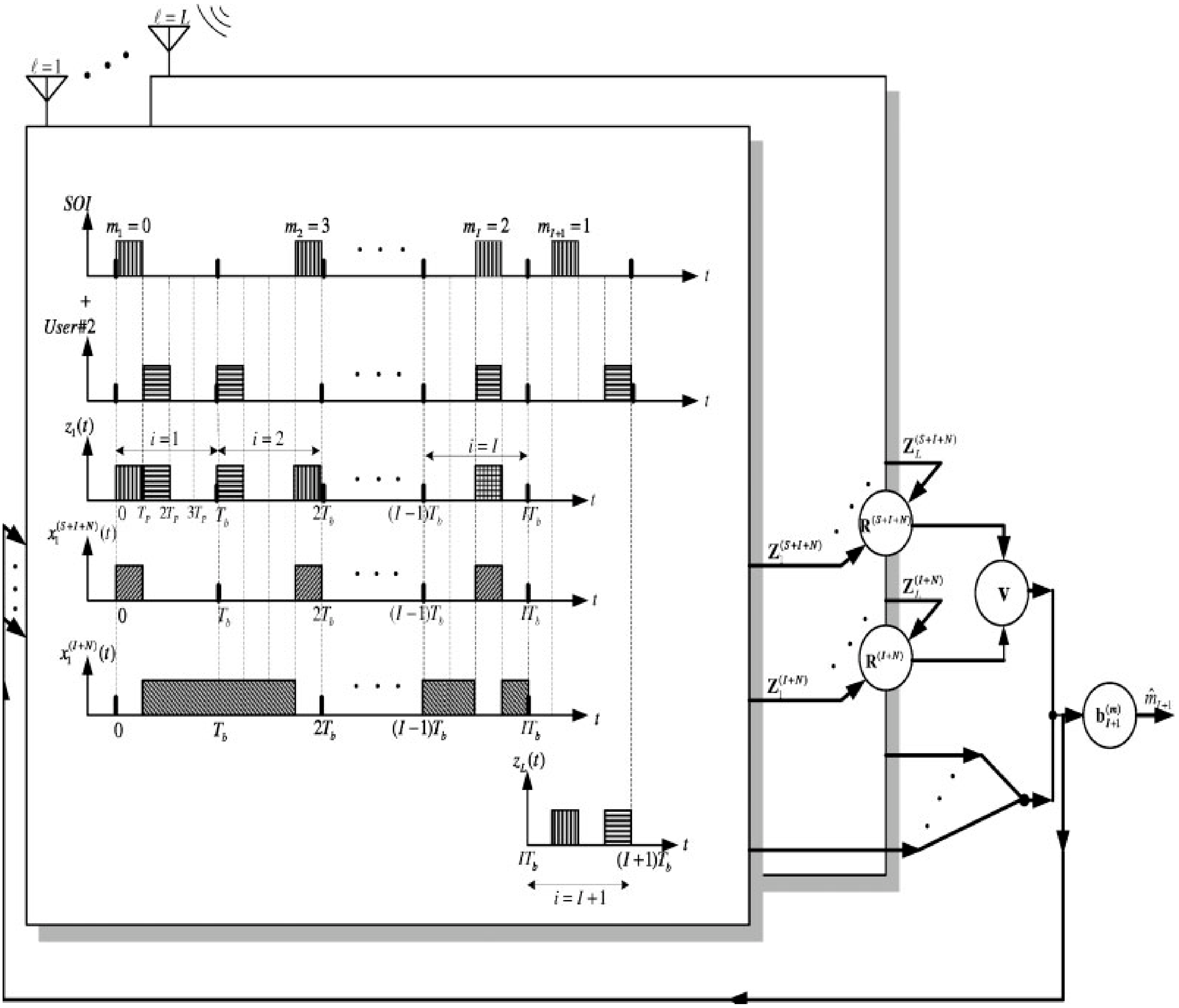

Figure 1. The collected data is segmented into two disjoint sets: the 'S + I + N' data-group and the 'I + N' data group for maximum-SINR 'blind' beamforming, to spatially combine the SOI's multipaths while suppressing the dominant co-channel interferers.

antennas' baseband-equivalent data and to suppress the unknown co-channel interference. This proposed spatial rake-receiver attempts to maximise the spatial beamformer's output's signal-to-interference-and-noise ratio (SINR).

Over the previous I (possibly *in*correctly) decoded information-symbols, there exist $I\frac{T_p}{T_s}$ number of 'S + I+ N' time-samples at the ℓth antenna. These time-samples are collected as the ℓth row $\mathbf{x}_\ell^{(S+I+N)}$ of the $L \times \frac{IT_p}{T_s}$ data-matrix $\mathbf{X}^{(S+I+N)}$. Similarly, a corresponding $I\frac{T_b-T_p}{T_s}$ number of 'I + N' time-samples exist at each antenna, to be collected into an $L \times I\frac{T_b-T_p}{T_s}$ data-matrix $\mathbf{X}^{(I+N)}$.

The proposed blind receiver scheme has the following additional algorithmic steps:

(i) Form the $L \times L$ spatial correlation matrices $\mathbf{R}_m^{(S+I+N)} = \mathbf{X}^{(S+I+N)}\left(\mathbf{X}^{(S+I+N)}\right)^H$ and $\mathbf{R}_m^{(I+N)} = \mathbf{X}^{(I+N)}\left(\mathbf{X}^{(I+N)}\right)^H$.

(ii) Find the principal generalised-eigenvector, $\mathbf{v}_m$, for the matrix-pencil pair $\{\mathbf{R}^{(S+I+N)}, \mathbf{R}^{(I+N)}\}$. This $L \times 1$ vector optimally sums the de-hopped baseband data in $\mathbf{X}^{(S+I+N)}$ to maximise the beamformer's output-SINR. That is, the SINR at the output of the beamforming weight vector $\mathbf{w}$ equals:

$$\mathrm{SINR}(\mathbf{w}) = \frac{\mathbf{w}^H\{\mathbf{R}^{(S+I+N)} - \mathbf{R}^{(I+N)}\}\mathbf{w}}{\mathbf{w}^H\mathbf{R}^{(I+N)}\mathbf{w}} \tag{3}$$

$$= \frac{\mathbf{w}^H\mathbf{R}^{(S+I+N)}\mathbf{w}}{\mathbf{w}^H\mathbf{R}^{(I+N)}\mathbf{w}} - 1 \tag{4}$$

$$\text{and} \quad \mathbf{v} \overset{\text{def}}{=} \arg \max_{\mathbf{w}} \left\{ \frac{\mathbf{w}^H\mathbf{R}^{(S+I+N)}\mathbf{w}}{\mathbf{w}^H\mathbf{R}^{(I+N)}\mathbf{w}} \right\} \tag{5}$$

(iii) Compute its beamformer output $b(n) = \|\mathbf{v}^H\mathbf{z}(nT_s)\|$ for $IT_b \leq nT_s < (I+1)T_b$.

(iv) Define $\mathbf{b}^{(m)}_{I+1} = \{b(jT_s), \forall m | T_p \leq jT_s < (m+1)T_p\}$ The $(I+1)$th transmitted information-symbol is estimated as

$$\hat{m}_{1,I+1} = \arg \max_{m \in \{0,\ldots,M-1\}} \left\{ \left\| \mathbf{b}^{(m)}_{I+1} \right\| \right\}$$

The above scheme needs no prior information about

(a) the SOI's arrival direction or power,
(b) any MAUI's arrival direction or relative arrival delay,
(c) the propagation channel's impulse response and
(d) the receiving antenna array's nominal or actual array-manifold—the antennas may have unknown and arbitrary gain/phase/polarisation responses and mutual coupling, possibly with statistically decorrelated or independent fading across the antennas (that is the channel fading may be uncorrelated from antenna to antenna).

4. SIMULATIONS

Simulation results presented in Figure 2 and Table 1 verify the efficacy of the proposed 'blind' spatial 'smart antennas' algorithm using decision-feedback (of the I preceding information-symbols, whose decoding might be incorrect). A pilot sequence of I information symbols (*a priori* known to the receiver) start off the decision feedback (which is based on possibly *in*correctly decoded information symbols) of a sequence of 10 000 information symbols. The following parameters apply for all simulations: An $M = 2$ alphabet encodes each PPM source, using no channel-encoding. $T_p = 6$ time-samples are taken of each PPM pulse. The PPM wireless communication system's active co-channel sources each have a signal arriving at the spatial-rake receiver, with an identical signal power and a complex-phase uniformly distributed between 0 to 2π radians. The SOI arrives from 90°; all MAUIs' arrival angles in each trial are randomised independently and uniformly over [0°, 180°] in Figure 2, but in [0°, 90°] Table 1. To illustrate the proposed scheme's applicability to an antenna-array of arbitrary geometric grid, the receiver uses a linear array of four identical omni-directional antennas, spaced respectively at 0, 1.1, 4.1 and 9 quarter-wavelengths from the origin.

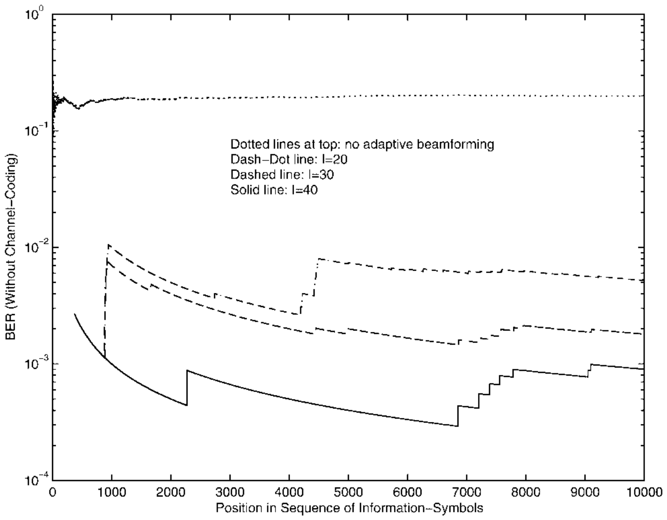

Figure 2. The proposed 'blind' RAKE receiver decision-feedback algorithm's BER up to each of the 10 000 information-symbols in the sequence, which is transmitted withOUT channel-encoding. The length of the pilot sequence varies from curve to curve, from 10 symbols to 40 symbols to start off the decision feedback. The SNR is 3 dB.

Figure 2 shows that as few as 40 pilot symbols in a 10 040-symbol sequence give a bit-error rate (BER) of only 0.0009, even withOUT channel encoding. These pilot symbols increase the transmission bandwidth by only $\frac{40}{10\,000} = 0.4\%$. As would be expected, a longer pilot

Table 1. The proposed 'blind' RAKE receiver decision-feedback algorithm's BER up to each of the 10 000 information-symbols in the sequence, which is transmitted withOUT channel-encoding. The receiver has four antennas. The SNR accounts only for the signal-of-interest and additive noise, not other transmitting sources in the system.

SNR	With three sources	With four sources	With five sources
−2 dB	0.2366	0.1757	0.5
0 dB	0.0028	0.0943	0.5
2 dB	0	0.0034	0.5
4 dB	0	0.0005	0.5
6 dB	0	0	0.5

sequence can produce a even lower BER. To highlight this proposed adaptive spatial-rake algorithm's MAUI suppression, Figure 2's dotted curves (at the figure's top) plot the BER obtained by a *non*-adaptive beamformer with weights $[1, 1, 1, 1]^T$, matching the SOI's direction-of-arrival from 90°. Such a non-adaptive beamformer requires additional prior information of the SOI's direction-of-arrival (which is not needed in the proposed scheme), but nonetheless has no MAUI-suppression capability and offers much inferior BER performance.

Table 1 illustrates how the number of incident sources and the additive noise's power level affect the proposed algorithm's performance. The pilot sequence here has 30 pilot symbols. The BER is for the entire 10 000-symbol sequence of information-symbols withOUT channel encoding. Table 1's zero BER values arise from the simulation's finite number of information-symbols. This pilot symbol increases the transmission bandwidth by only $\frac{30}{10\,000} = 0.3\%$. The SOI's BER is identically zero with three interfering sources at SNR equal 6 dB. This 4-antenna array cannot handle more than four sources.

5. CONCLUSION

Herein proposed is a new semi-'blind' spatial-rake receiver with decision feedback initiated by a short pilot sequence from the SOI. This interference-rejecting beamformer requires no prior knowledge of (1) the multi-user co-channel interferers' arrival directions, delays nor powers, (2) the (SOI) spatial signature on the receiving sensor-array and (3) the mobile's receiving-antennas' nominal/actual array-geometry and gain/phase responses.

REFERENCES

1. Anderson F, Christensen W, Fullerton L, Kortegaard B. Ultra-wideband beamforming in sparse arrays. *IEEE Proceedings: Microwave, Antennas & Propagation* 1991; **H-138**(4):342–346.
2. Hussain MGM, Yedlin MJ. Active-array beamforming for ultra-wideband impulse radar. *IEEE Radar Conference* 2000; pp. 267–272.
3. Heidary K. Ultra-wideband antenna array. *IEEE Antennas-Propagation Society International Symposium* 2001; 472–475.
4. Foo S, Kashyap S. Time domain array factor for UWB antenna array. *IEEE Electronics Letters* 2003; **39**(18):1304–1305.
5. Choi JD, Stark WE. Performance of ultra-wideband communications with suboptimal receivers in multipath channels. *IEEE Journal on Selected Areas in Communications* 2002; **20**(9):1754–1766.
6. Hussain MGM. Principles of space-time array processing for ultrawide band impulse radar and radio communications. *IEEE Transactions on Vehicular Technology* 2002; **51**(3):393–403.
7. Tan S-S, Kannan B, Nallanathan A. Performance of ultra-wideband time-hopping spread spectrum impulse radio systems with antenna array. *IEEE International Conference on Communication Systems* 2002; **1**:399–403.
8. Tan S-S, Kannan B, Nallanathan A. Performance of UWB multiple access impulse radio systems in multipath environment with antenna array. *IEEE Global Telecommunications Conference* 2003; **4**:2182–2186.
9. Wong KT. Radiowave PPM blind spatial-rake receiver & co-channel interference suppression. *IEEE Annual Canadian Conference on Electrical & Computer Engineering* 2005; 1606–1609.
10. Zoltowski MD, Ramos J. Blind adaptive beamforming for narrowband co-channel digital communications signals in a multipath environment. *IEEE International Conference on Acoustics, Speech, and Signal Processing* 1995; **3**:1745–1748.
11. Wong KT, Tichavsky P. A reduced-complexity 'blind' space-frequency algorithm for peer-to-peer MFSK-FFH-CDMA detection & co-channel interference suppression. *IEEE Global Telecommunications Conference* 2003; **5**:2437–2441.
12. Wong KT, Cheung SK. Fractional self-Decorrelation to enhance single-user-type DS-CDMA detectors' output SINR in blind space-time RAKE receivers. *IEEE Communications Letters* 2004; **8**(6):336–338.
13. Tichavsky P, Wong KT. Analytical derivation of finite-data-record performance of Wong-Lok-Lehnert-Zoltowski's DS-CDMA blind space-time receiver. *IEEE Transactions on Signal Processing* 2005; **53**(4):1485–1499.

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