TIME-FREQUENCY DECISION-DRIVEN MULTIUSER DETECTORS OVER FAST-FADING MULTIPATH CHANNELS FOR SYNCHRONOUS DS-CDMA SYSTEMS

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Abstract - *RAKE receivers suffer degradation in performance under fast fading due to errors in channel state estimation. The wide-sense stationary uncorrelated scatterer channel model lends itself to time-frequency canonical representation, and provides additional diversity in the frequency axis. That is, the joint multipath-Doppler diversity model enables the development of nonlinear decision-driven time-frequency multiuser detectors based on successive interference cancellation and multistage interference cancellation ideas. Simulation results demonstrate that the proposed nonlinear decision-driven time-frequency multiuser detectors promise substantially improved bit-error-rate performance compared to previously proposed time-frequency multiuser detectors while exhibiting strong resistance to the near-far effect.*

I. INTRODUCTION

Multipath fading often presents a major limitation to CDMA system performance. The conventional approach to data detection on slow-fading multipath channels is to employ an independent single-user *RAKE receiver* for each user, however the RAKE receiver suffers from the near-far effects in the presence of MAI. Additionally, the RAKE receiver used in existing systems suffers from significant performance degradation due to the rapid channel variations encountered under fast fading. The increased mobility of users in cellular communications often results in fast fading in which the channel exhibits rapid temporal variations and the resulting Doppler spread induced in the signal substantially degrades the performance of the RAKE receiver due to the errors in the channel state estimation.

Recently, in a series of papers [3, 5, 4, 1, 2], a new framework that is directly inspired by the characteristics of fast-fading multipath channels is proposed. The key idea behind this approach is to fully exploit the *joint multipath-Doppler diversity* [1] in order to provide another means for diversity, in conjunction with multipath diversity. Such a formulation can yield significant gains via appropriate signalling and reception even with relatively small Doppler spreads encountered in practice.

*This work is supported by Turkish Scientific and Technological Research Council.

[1] Doppler effects are the major sources of degradation in conventional systems

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Time-frequency joint multipath-Doppler diversity is exploited using a time-frequency RAKE demodulator front-end which correlates the received signal with time (multipath) and frequency (Doppler) shifted copies of the spreading waveform. Examining the time-frequency RAKE receiver front-end, it can be seen that the sufficient statistics incorporates a spurious MAI term. Using interference cancellation techniques such as SIC (sucessive interference cancellation) and multistage interference cancellation, the spurious MAI term in the statistics can be cancelled by exploiting the internal tentative decisions that are provided by a previous signal processing stage [2]. In this paper, this is our viewpoint and methodology in derivation and analysis of new nonlinear decision-driven time-frequency multiuser detectors based on joint multipath-Doppler processing framework.

The next section presents the CDMA system model considered and the time-frequency joint multipath-Doppler processing framework. In Section III, we derive nonlinear decision-driven time-frequency multiuser detectors based on joint multipath-Doppler processing. Section IV presents the numerical results that illustrates the potential performance gains of the proposed detectors and Section V contains our conclusions.

II. SYSTEM MODEL

The time-frequency joint multipath-Doppler processing framework is mainly built on the time-frequency representations (TFRs) which are jointly parametrized by both time and frequency making them ideally suited for processing signals transmitted over inherently time-varying mobile wireless channels. Restricting the discussion firstly to the single-user case, binary antipodal signalling (BPSK), negligible intersymbol interference and perfect synchronization, the baseband signal $r(t)$ at the receiver for a synchronized single-user with binary antipodal signalling is given by:

$$r(t) = s(t) + n(t) = \int_0^\infty h(t,\tau)x(t-\tau)d\tau + n(t), \quad (1)$$

where the channel is described by the kernel $h(t,\tau)$ which corresponds to a time-varying linear system, and n(t) is complex AWGN with power spectral density N_0.

[2] Given that the internal tentative decisions are correct which is typical at high SNR.

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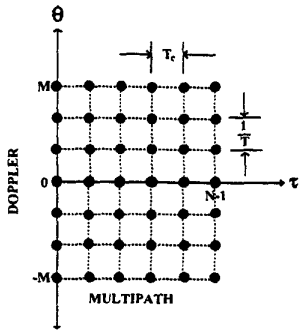


Figure 1: Sampling of the time-frequency plane inherent in the canonical channel representation.

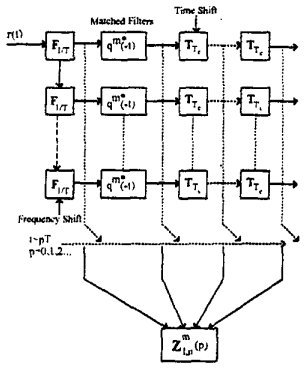


Figure 2: Implementation of sampled STFT using a bank of time-frequency matched filters.

Following the approach in [3], we can find that the received signal consists of a linear combination of time-shifted (multipath) and frequency-shifted (Doppler) copies of the transmitted signal. The following theorem whose proof can be found in [5] describes a canonical representation of the channel and the received signal that plays a fundamental role in the time-frequency joint multipath-Doppler processing framework:

Theorem. The received signal s(t) in (9) admits the finite-dimensional representation:

$$s(t) \approx \frac{T_c}{T} \sum_{n=0}^{N} \sum_{l=-M}^{M} \hat{H}(\frac{l}{T}, nT_c)\, u_{l,n}(t), \qquad (2)$$

where $N = \lceil T_m/T_c \rceil \approx \lceil T_m B \rceil$, $M = \lceil B_d T \rceil$, and $\hat{H}(\theta,\tau)$ is a smoothed version of $H(\theta,\tau)$. The basis waveforms $u_{l,n}(t)$ are defined as:

$$u_{l,n}(t) = (F_{\frac{l}{T}} T_{nT_c} q)(t) = q(t - nT_c) e^{\frac{j2\pi lt}{T}}, \qquad (3)$$

where $q(t)$ is the spreading waveform and the basis waveforms are approximately orthogonal to each other. Figure 1 represents the sampling of the time-frequency plane inherent in the canonical channel representation of (2).

The representation (2) also identifies the matched-filter waveforms needed to extract the independent multipath-Doppler components:

$$u^m_{l,n}(t) = (\mathbf{F}_{\frac{l}{T}} \mathbf{T}_{nT_c} q^m)(t) = q^m(t - nT_c) e^{j\frac{2\pi lt}{T}},$$
$$l = -M, ..., 0, ..., M,\ n = 0, 1, ..., N-1., \qquad (4)$$

It can be seen that the matched filter outputs can be precisely computed via sampled short-time Fourier transforms, or in other words through a time-frequency RAKE front-end consisting of time-frequency correlators; whose sufficient statistics are given by [4]:

$$\langle r, u^m_{l,n} \rangle = \mathbf{STFT}_r(\frac{l}{T}, nT_c; q^m), \qquad (5)$$

Figure 2 illustrates the implementation of the time-frequency RAKE demodulator via sampled STFTs.

Reverting back to the multiuser scenario, for a CDMA system with K users employing synchronous coherent BPSK signalling over fast-fading multipath channel and for negligible intersymbol interference ($T_m << T$) where the one-shot detector suffices, the output of the time-frequency correlators of the RAKE demodulator front-end for an arbitrary signalling interval is given by:

$$\mathbf{z} = \mathbf{RHb} + \mathbf{w}, \qquad (6)$$

where Hermitian correlation matrix $\mathbf{R}$ is given by:

$$\mathbf{R} = \int \mathbf{s}^*(t)\mathbf{s}^T(t)dt = \begin{bmatrix} \mathbf{Q}_{11} & \mathbf{Q}_{12} & \cdots & \mathbf{Q}_{1K} \\ \mathbf{Q}_{21} & \mathbf{Q}_{22} & \cdots & \mathbf{Q}_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{Q}_{K1} & \mathbf{Q}_{K2} & \cdots & \mathbf{Q}_{KK} \end{bmatrix}, \qquad (7)$$

and defining the dimension of joint multipath-Doppler diversity as $D_p = (N+1)(2M+1)$, the channel matrix $\mathbf{H}$ can be defined in terms of the channel coefficients $H^{ln}_k(i)$'s as a KD_p xK matrix as:

$$\mathbf{H}(i) = \begin{bmatrix} \mathbf{h}_1(i) & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{h}_2(i) & \mathbf{0} & \cdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{h}_K(i) \end{bmatrix}, \qquad (8)$$

where $\mathbf{h}_k(i)$ is D_px1 channel coefficients vector for the ith bit of the kth user and the Kx1 vector for the ith bit is defined as:

$$\mathbf{b}(i) = [b_1(i), b_2(i), ..., b_K(i)]^T, \qquad (9)$$

The zero-mean complex Gaussian noise vector $\mathbf{w}$ is of dimension KD_px1 with cross-correlation matrix $E[\mathbf{ww}^H] = N_0\mathbf{R}$.

For the sake of simplicity, we consider the two-user case in the sequel. Explicitly writing the Hermitian cross-correlation matrix $\mathbf{R}$, the D_px1 sufficient statistics vectors provided by the time-frequency RAKE demodulator front-end for two users can be expressed as:

$$\mathbf{z}^{ln}_1(p) = b_1\mathbf{Q}_{11}\mathbf{h}_1 + b_2\mathbf{Q}_{22}\mathbf{h}_2 + n_1 = b_1\mathbf{g}_1 + \mathbf{i}_1 + \mathbf{n}_1, \qquad (10)$$

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$$\mathbf{z}_2^{\ln}(p) = b_2\mathbf{Q}_{22}\mathbf{h}_2 + b_1\mathbf{Q}_{11}\mathbf{h}_1 + n_2 = b_2\mathbf{g}_2 + \mathbf{i}_2 + \mathbf{n}_2, \quad (11)$$

where $\mathbf{Q}_{k\acute{k}}$ is the D_pxD_p Hermitian correlation matrix between the time-frequency shifted waveforms of users k and $\acute{k}$, $\mathbf{h}_1$ and $\mathbf{h}_2$ are the channel coefficient vectors of user 1 and 2 respectively, and $\mathbf{n}_1$ and $\mathbf{n}_2$ are D_px1 complex Gaussian noise vectors with cross-correlation matrices $E[\mathbf{n}_1\mathbf{n}_1^H]=\sigma^2\ \mathbf{Q}_{11}$ and $E[\mathbf{n}_2\mathbf{n}_2^H]=\sigma^2\mathbf{Q}_{22}$ respectively. It can be easily seen that the sufficient statistics are composed of a useful signal component, a sprurious MAI component and background noise.

In the absence of multiaccess interference which corresponds to the single-user case, the optimal receiver is the TF-RAKE receiver with maximal-ratio-combining. However, maximal-ratio-combining is optimal when the coherently combined statistics are white; therefore a prewhitening operation is needed. The whitening matrix for the kth user is given by:

$$\mathbf{W_k} = (diag\ (\mathbf{Q}_{kk}))^{-\frac{1}{2}}, \quad (12)$$

Referring to the whitened statistics for the kth user as $\mathbf{z}_k^w$, the single-user TF-RAKE receiver with maximal-ratio-combining is given by:

$$\hat{b}_k = sign\left\{Re[\mathbf{h}_k\mathbf{z}_k^w]\right\} = sign\left\{Re[\sum_{l=0}^{N}\sum_{n=-M}^{M} H_k^{*\ln} z_k^{w-\ln}]\right\},$$

$$k = 1, 2, ..., K, \quad (13)$$

TF-RAKE receiver with maximal-ratio-combining is optimal in the single user case, however in the multiuser case, it is not near-far resistant since it ignores the multiaccess interference. Motivated with this degradation of TF-RAKE receiver with MRC under near-far situations, near-far resistant structures based on a TF-RAKE front-end is previously sought in the literature. Time-frequency optimum maximum-likelihood, time-frequency decorrelator and time-frequency MMSE structures which augments the TF-RAKE receiver with MRC by suppressing the multiaccess interference are derived in [1, 2]. As in AWGN counterpart, the computational complexity of the time-frequency optimum maximum-likelihood receiver is exponential in the number of users, therefore suboptimal approaches are sought in [1, 2], and the time-frequency decorrelator and time-frequency MMSE receivers are derived whose computational complexity is linear in the number of users.

If the maximum-likelihood estimate of **Hb** is sought, the resulting receiver time-frequency decorrelator is linear and constitutes a generalization of the decorrelating receiver with the estimator matrix $\mathbf{F}_{ML} = R^{-1}$ [1]. The transformed noise vector after decorrelation is correlated and a prewhitening operation is required before MRC. The time-frequency decorrelator structure is then given by $\hat{\mathbf{b}}_{dec} = sign\left\{Re[\mathbf{H}^H\mathbf{W}\mathbf{R}^{-1}\mathbf{z}]\right\}$ where **W** and **H** performs the whitening and maximal-ratio diversity combining respectively.

Similar to the time-frequency decorrelator structure, an MMSE based detector is derived in [2]. After time-frequency RAKE front-end processing and obtaining the sufficient statistics in (10) and (11), the minimum-mean-square-error formulation of [2] tries to solve the minimization problems to obtain the linear MMSE filter vectors that minimize the mean-square-error between the transmitted bit of the kth user and the processed statistics. The expressions for the linear MMSE filter vectors obtained as the solution to the minimization problems are given by $\mathbf{f_{k,mmse}} = \mathbf{R}_{z_k z_k}^{-1}\mathbf{g}_k$ where $\mathbf{R}_{z_k z_k}$ is the correlation matrix of the sufficient statistics for kth user. The MMSE estimates of the bits are then obtained by thresholding the inner product of these linear MMSE filter vectors with sufficient statistics for each user.

III. TIME-FREQUENCY NONLINEAR DECISION-DRIVEN MULTIUSER DETECTORS

Interference cancellation is one of the oldest ideas in communication theory, and we exploit this idea in this section to derive new decision-driven multiuser detectors based on joint multipath-Doppler processing approach. The technique of successive interference cancellation is based on a natural and simple idea: if a decision has been made about an interfering user's bit, then that interfering signal can be recreated at the receiver and subtracted from the received waveform. This will cancel the interfering signal provided that the decision was correct; otherwise it will double the contribution of the interferer. Once the subtraction has taken place, the receiver takes the optimistic view that the resulting signal contains one fewer user and the process can be repeated with another interferer, until all but one user have been demodulated. In order to fully describe the receiver we just need to specify how the intermediate tentative decisions are obtained. Since erroneous intermediate tentative decisions affect the reliability of all successive decisions, successive interference cancellation (SIC) receivers need to order the users generally in terms of descending received energies to optimally decode the users.

Other interference cancellation methods proposed previously in the literature are multistage interference cancellation and parallel interference cancellation (PIC) which both does not require a sorting of the users in descending received energies as MAI is cancelled in all user branches using tentative decisions of a previous stage irrespective of the energies.

Recalling from (10) and (11), sufficient statistics provided by the time-frequency RAKE demodulator is comprised of a useful signal component, a spurious MAI component and a background noise component. Our approach is that near-far resistant time-frequency successive interference cancellation and time-frequency multistage receivers can be obtained by using intermediate tentative decisions on the bits of interfering users to cancel the MAI component. The approach is viable as the MAI component can be regenerated exactly at the receiver through the knowledge of the correlation matrices and the channel coefficients. Time-frequency succesive interference cancellation receiver (TF-SIC) is depicted in Figure 3. In all receiver figures, a bold line represents a D_px1 dimensional vectorial flow of either sufficient statisitics provided by TF-RAKE front end or their processed versions. Under the light of assumption that the received energy of the second user is higher than that of the first user ($\| \mathbf{g}_2 \|^2 > \| \mathbf{g}_1 \|^2$),the second user is demodulated and

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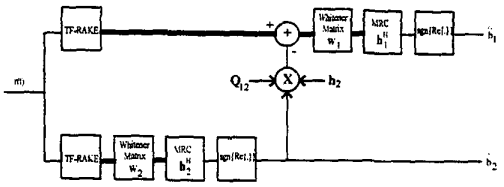


Figure 3: Time-Frequency Successive Interference Cancellation (TF-SIC) Multiuser Receiver.

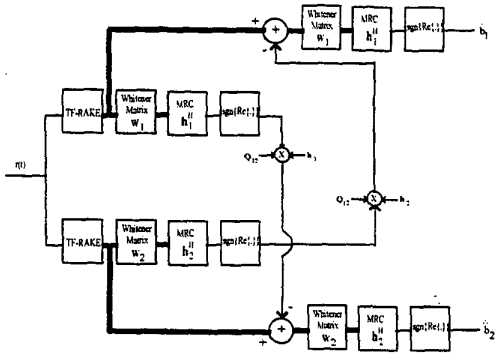


Figure 4: Time-Frequency Multistage Coventional TF-RAKE First Stage (TF-MS-CONVFS) Multiuser Receiver.

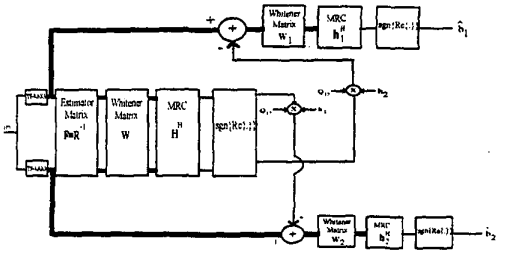


Figure 5: Time-Frequency Multistage Decorrelator First Stage (TF-MS-DECFS) Multiuser Receiver.

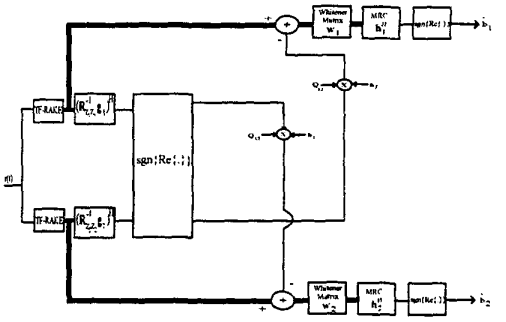


Figure 6: Time-Frequency Multistage MMSE First Stage (TF-MS-MMSEFS) Multiuser Receiver.

detected firstly by a TF-RAKE receiver with MRC and this bit estimate for the second user is used to generate the MAI estimate in first user 's statistics due to the second user: $\hat{\mathbf{i}}_1=\hat{\mathbf{b}}_2\mathbf{Q}_{12}\mathbf{h}_2$. After cancellation of this estimate from the statistics, the first user's bit is detected with whitening, maximal-ratio-combining and thresholding on the striped statistics.

The difference of the multistage interference cancellation from successive interference cancellation is that the MAI in all user statistics is cancelled using the tentative decisions of a previous stage. A TF-RAKE receiver with MRC, a time-frequency decorrelator or a time-frequency MMSE are possible candidates for the first stage which generate the intermediate tentative decisions. Figures 4,5 and 6 depict the structure of time-frequency multistage conventional TF-RAKE first stage (TF-MS-CONVFS), time-frequency multistage decorrelator first stage (TF-MS-DECFS) and time-frequency multistage MMSE first stage (TF-MS-MMSEFS) multiuser detectors respectively. The initial stage provides the tentative estimates, the MAI components are then regenerated and cancelled from the statistics followed by a second detection stage via whitening, maximal-ratio-combining and thresholding on the striped statistics.

IV. NUMERICAL RESULTS

The objective of this section is to present the potential performance gains of the proposed nonlinear decision-driven time-frequency multiuser detectors through simulation studies. The spreading waveforms used in the simulations are obtained from a Gold-code set of processing gain 7. For the data rate 10 Khz, carrier frequency 1800 MHz and maximum vehicle speed of 50 mph, the corresponding resolved multipath components, resolved Doppler components, the multipath spread and the Doppler spread is tabulated in Table 1 for each D_p used in the simulations. Monte Carlo simulations are performed for each data point averaging over 10000 independent experiments.

The bit-error-rates of multiuser detectors at D_p=6 are presented in Figure 7. The single-user TF-RAKE with MRC receiver provides the lower bound on the performance curves. Simulation results show that at high SNR time-frequency MMSE outperforms time-frequency decorrelator and all proposed nonlinear decision-driven time-frequency multiuser detectors outperform time-frequency decorrelator and time-frequency MMSE detectors.

Figure 8 depicts the bit-error-rates versus near-far

D_p	M	D	T_m (msec)	B_d (KHz)
1	1	1	0.014	10
3	1	3	0.014	30
6	2	3	0.028	30
15	3	5	0.042	50

Table 1: Multipath Components (M), Doppler Components (D), Multipath Spread and Doppler Spread Corresponding to Each D_p Used in the Simulations.

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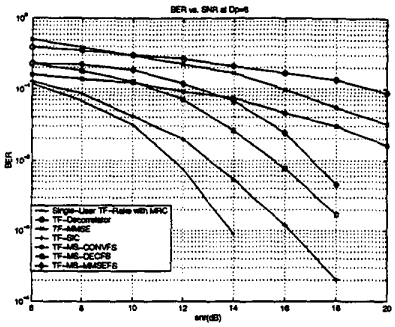


Figure 7: Simulated Bit-Error-Rates vs. SNR at $D_p = 6$.

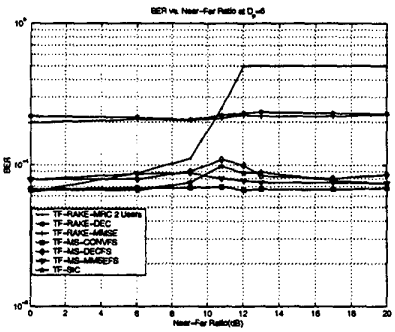


Figure 8: Simulated Bit-Error-Rates vs. MAI at $D_p = 6$.

ratio when the SNR of first user is 8 dB. TF-RAKE with MRC receiver with two users suffers from the near-far effect and exhibit an increasing bit-error-rate performance with near-far ratio while the proposed nonlinear decision-driven time-frequency multiuser detectors also maintain an almost constant bit-error-rate performance indicating resistance to near-far effect.

Figure 9 presents the potential performance gains of joint multipath-Doppler processing. The bit-error-rate performance of the proposed nonlinear decision-driven time-frequency multiuser detectors are shown versus SNR at $D_p = 1$ and $D_p = 6$. D_p=1 corresponds to the time-nonselective frequency-nonselective channel where no diversity is available. All proposed detectors exhibit siginificantly improved BER performance at $D_p = 6$ with respect to D_p=1 indicating the preservation of the inherently higher level of diversity gains afforded by the time-frequency joint multipath-Doppler processing.

V. CONCLUSIONS

Central to modern mobile communication networks is the fast fading multipath wireless channel which is one of the single most important factors affecting the system performance. For optimal processing, time-varying signal processing techniques are needed to account for the inherently time-varying dynamics of the channel. Using the joint multipath-Doppler diversity framework that is dictated by a canonical representation of the wide-sense stationary uncorrelated scatterer channel model, we derived nonlinear decision-driven time-frequency multiuser detectors based on successive interference cancellation and multistage interference cancellation ideas which achieve suppression of the multiaccess interference component in the sufficient statistics provided by the time-frequency RAKE demodulator front-end. Simulation results based on realistic fast fading assumptions demonstrated that the proposed nonlinear decision-driven time-frequency multiuser detectors promise substantially improved bit-error-rate performance compared to the time-frequency decorrelator and the time-frequency MMSE multiuser detectors while exhibiting strong resistance to the near-far effect. The proposed detectors preserved the gains of inherently higher level of diversity gains afforded by the time-frequency joint multipath-Doppler processing and the time-complexity-per-bit of the proposed multiuser detectors are linear in the number of users.

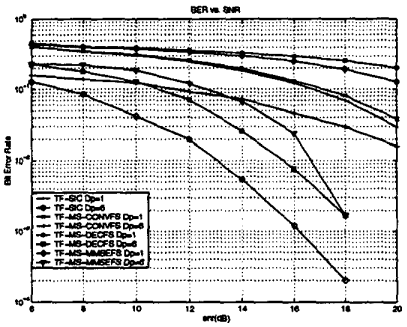


Figure 9: Simulated Bit-Error-Rates of Decision-Driven Time-Frequency Multiuser Detectors vs. SNR at different diversity levels.

References

[1] B. Aazhang A. M. Sayeed and Andrew Sendonaris. Multiuser detection in fast-fading multipath environments. *IEEE Journal on Selected Areas in Communications*, vol. JSAC-16:1691–1701, December 1998.

[2] T. Kadous and A. M. Sayeed. Decentralized multiuser detection for time-varying multipath channels. Submitted to IEEE Transactions on Communications, July 1999.

[3] A. M. Sayeed. Canonical multipath-doppler coordinates in wireless communications. In *36th Annual Allerton Conference*, September 1998.

[4] A. M. Sayeed and B. Aazhang. Communication over multipath fading channels: A time-frequency perspective. In *PIMRC'97*, September 1997.

[5] A. M. Sayeed and B. Aazhang. Joint multipath-doppler diversity in mobile wireless communications. *IEEE Transactions on Communications*, vol. COMM-47:123–132, January 1999.

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