A MULTIUSER APPROACH TO MINIMUM-ERROR-PROBABILITY DETECTION FOR NARROWBAND MULTIPLE ACCESS DATA-SYSTEMS AFFECTED BY ISI AND CCI

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Abstract

In this contribution, novel Symbol-by-Symbol (SbS)-type Maximum A posteriori Probability (MAP) receivers are presented for non Spread-Spectrum (SS) Multiple-Access (MAC) narrowband systems impaired by ISI and Co-Channel Interference (CCI). The proposed decentralized-type receivers minimize the error probability in the detection of the desired user message on a per-symbol basis. A practical application environment for the presented receivers can be constituted by Ethernet-type Local Area Networks (LANs) where central offices are linked to subscribers via multitapped buses.

1. Motivation of the Work

The fast increasing traffic-loads experienced in the last years by MAC systems make the available system-band a very precious resource that must be efficiently exploited. Since conventional SS-CDMA systems based on orthogonal signature-sequences [7, Chap.6] are inherently bandwidth-inefficient [4,10], several alternative non-SS CDMA techniques have been recently proposed [10]. These techniques utilize a suitable form of coding [3,5] and/or precoding [1,4] so as to obtain good performance without wasting the available band.

Obviously, the ultimate performance of an MAC system also depends on the approach adopted to detect the CCI-affected received signal. At this regard, it is experienced that *decentralized-type* multiuser receivers [2] generally exhibit a good tradeoff between the two contrasting requirements of reliable performance and low implementation complexity [1,2,5 and references therein]. In essence, these receivers *carefully exploit* the statistical features of the CCI but track and detect *only* the message of the desired user so that their implementation is attractive especially for the subscribers of MAC systems [1,2,5].

On the basis of the above system-considerations, in the present contribution we focus on decentralized-type multiuser receivers for *ISI and CCI-impaired* narrowband (non-SS) bandwidth-efficient MAC data-systems. The novel detectors we present minimize the error probability on a *per-symbol basis* and, thus, they can be considered as the natural extension to CCI-impaired environments of the standard SbS-MAP Abend-Fritchman type receivers [8] for CCI-free and ISI-affected environments. More in detail, after the modeling of the system carried out in Sect.2, the optimum SbS-MAP receiver that *fully exploits* the statistical features of the CCI is presented in Sect.3. Afterwards, in the following Sects.4, 5 two simplified versions of the optimum receiver are developed for the two complementary-type cases of discrete-valued memoryless CCI and colored Gaussian CCI. The actual effectiveness of the proposed detectors is tested in the conclusive Sect.6 via numerical examples.

2. Modeling of Narrowband Multiple Access Systems

The baud-rate sampled lowpass (complex) version of the considered narrowband ISI-corrupted MAC system is sketched in Fig.1 where $\{a(n)\in A\}$ and $\{a^{(i)}(n)\in A\}$, $1 \le i \le L$, represent the data-streams generated by the desired user and the L interfering ones at a common signaling-period T. These (L+1) data streams are assumed zero-mean, unitary variance, mutually independent and their equi-distributed outcomes take values on an assigned q-ary QAM complex constellation $A\equiv\{\alpha_1,\dots,\alpha_q\}\subset C$. After the amplifications introduced by the (deterministic) non-negative transmitting gains G and $G^{(i)}$, $1 \le i \le L$, the desired and interfering streams cross the corresponding ISI-channels so that the T-sampled noisy, CCI and ISI-corrupted (complex) received sequence $\{r(n)\in C\}$ can be modeled as

$$r(n) \equiv G\sum_{l=0}^{L_C-1} h(l)a(n-l) + \sum_{i=1}^{L} u^{(i)}(n) + w(n) = \qquad (1)$$

$$= u(n) + \mu(n) + w(n), \qquad (2)$$

where $\{u(n)\}$ is the ISI-corrupted desired sequence,

$\{\mu(n)\}$ is the (ISI-impaired) CCI sequence and $\{w(n)\}$ is a complex AWGN whose uncorrelated components share the same variance $N_o/2$. Therefore, after introducing the (L+1) channel-state sequences

$$\sigma(n) \equiv \left[a(n)\dots a(n-L_c+1)\right]^T \in A^{L_c} \equiv \equiv A_\sigma \equiv \left\{\xi_1 \dots \xi_{N_\sigma}\right\} \subset C^{L_c}, \left(N_\sigma \equiv q^{L_c}\right), \quad (3)$$

$$\sigma^{(i)}(n) \equiv \left[a^{(i)}(n)\dots a^{(i)}(n-L_c^{(i)}+1)\right]^T \in A^{L_c^{(i)}} \equiv \equiv A_\sigma^{(i)} \equiv \left\{\xi_1^{(i)} \dots \xi_{N_\sigma^{(i)}}^{(i)}\right\} \subset C^{L_c^{(i)}}, \left(N_\sigma^{(i)} \equiv q^{L_c^{(i)}}\right), \quad (4)$$

we can equivalently re-write the relationships in (1) as

$$r(n) \equiv Gh^T\sigma(n) + \sum_{i=1}^{L} G^{(i)} {h^{(i)}}^T \sigma^{(i)}(n) + w(n) \equiv \equiv u(n) + \mu(n) + w(n),\, n \ge 1, \quad (5)$$

with the positions $h \equiv \left[h(0)\dots h(L_C-1)\right]^T$ and $h^{(i)} \equiv \left[h^{(i)}(0)\dots h^{(i)}(L_c^{(i)}-1)\right]^T$. Now, the above mutually independent channel-state sequences $\{\sigma(n)\in A_\sigma\}$ and $\{\sigma^{(i)}(n)\in A_\sigma^{(i)}\}$, $1 \le i \le L$, are stationary multivariate Markov chains that evolve as the states of (L+1) right-shifted-registers of lengths L_c and $L_c^{(i)}$, $1 \le i \le L$, respectively; so, in the sequel we indicate as Φ_σ and $\Phi_\sigma^{(i)}$, $1 \le i \le L$, the corresponding usual transition-probability (square) matrices [8].

From a practical point of view, the most appealing feature of the considered non-SS MAC system of Fig.1 is its large spectral-efficiency η_{NB} that grows linearly with the users' number (L+1) according to the relationship:

$$\eta_{NB} = \left[\left(L+1\right)/\left(1+\beta\right)\right]\log_2 q, \text{bits/sec/Hz.}$$

where $\beta\in[0,1]$ is the value of the roll-off factor of the front-end filters present in the considered MAC system. Since the corresponding spectral-efficiency η_{SS-O} of a conventional SS-CDMA system which employ orthogonal (Walsh-Hadamard type) signature sequences for their (L+1) users is upper-bounded by (see [7,Sect.6.7.3]): $\eta_{SS-O} = \log_2 q/\left(1+\beta\right)$ (bits/sec/Hz), the design and optimization of a *non*-SS MAC system such as that depicted in Fig.1 have received growing interest in the last years (see, for example, [3,4,5] and therein references). More in detail, the ultimate goal of the SbS-MAP receiver present in the narrowband system sketched in Fig.1 is to deliver the $D\equiv(L_c\text{-}1)$-delayed minimum-error-probability detected stream $\{\hat{a}(n\text{-}L_c\text{+}1)\}$ for the *desired* user by working in accordance with the usual MAP decision rule (see [8]).

Now, it is known [8 and references therein] that an application of the Total Probability Theorem allows us to compute the A Posteriori Probabilities (APPs) in (7) by linearly combining the elements of the vector $\pi(n/n) \equiv \left[P\left(\sigma(n)=\xi_1/r_1^n\right)\dots P\left(\sigma(n)=\xi_{N_\sigma}/r_1^n\right)\right]^T$ of the APPs of the state-chain $\{\sigma(n)\}$ of the desired channel in (3) according to the simple relationship ($1 \le m \le q$) [8]:

$$P\left(a(n-L_C+1)=\alpha_m/r_1^n\right) = \sum_{k\in A(m)} P\left(\sigma(n)=\xi_k/r_1^n\right)$$

where the vector $r_1^n \equiv \left[r(1)\dots r(n)\right]^T$ gathers the received samples of eq.(5) until step n, $A(m)\subseteq A_\sigma$ is the set (of size $q^{(Lc-1)}$) constituted by the outcomes $\{\xi_k\}$ in (3) with the m-th component equal α_m. Therefore, the computation of the detected stream $\{\hat{a}(n\text{-}(L_c\text{-}1))\}$ for the desired user can be carried out on the basis of the above defined APP sequence $\left\{\pi(n/n), n \ge 1\right\}$ and, in turn, this last can be obtained via several algorithms whose resulting complexities greatly depend on the approximations introduced to describe the actual statistical behavior of the CCI sequence $\{\mu(n)\}$ (see, for example, [1,2] for some general interesting considerations about this topic).

The simplest SbS-MAP decentralized-type detector we can derive, models the CCI sequence $\{\mu(n)\}$ as an additional (complex) Gaussian noise of variance $\sigma_\mu^2 \equiv \sum_{i=1}^{L}\left(G^{(i)}\right)^2$ so that the recursive computation of the above introduced APP vector $\left\{\pi(n/n)\right\}$ can be carried out via the standard Abend-Fritchman algorithm in accordance to the following relationships:

$$\pi(n/n-1) \equiv \left[P\left(\sigma(n)=\xi_1/r_1^{n-1}\right)\dots P\left(\sigma(n)=\xi_{N_\sigma}/r_1^{n-1}\right)\right]^T = = \Phi_\sigma\, \pi(n-1/n-1), n \ge 2, \text{ with } \pi(1/0) = \left(N_\sigma\right)^{-1}\underline{1}_{N_\sigma} \quad (6)$$

$$\Delta_C(r(n)) \equiv diag\left\{\dots, \exp\left\{-\frac{\left\|r(n)-Gh^T\xi_1\right\|^2}{\sigma_\mu^2+N_O}\right\},\dots\right\},$$

$$\pi(n/n) = \frac{\Delta_C(r(n))\pi(n/n-1)}{\left(\underline{1}_{N_\sigma}\right)^T \Delta_C(r(n))\pi(n/n-1)}, n \ge 1.$$

Obviously, the complexity of the above SbS-MAP decentralized detector is *fully* independent from the number L of the interfering users and its implementation only requires the knowledge of the impulse response of the desired channel Gh, the CCI level σ_μ^2 and the noise level N_o. However, this detector *does not exploit at all* the actual statistics of the CCI sequence $\{\mu(n)\}$ so that it results deeply *CCI-limited* and for medium to low SIRs its performance is very poor even for high SNRs (see Sect.6).

3. The proposed Optimum SbS-MAP Detector for Narrowband Multiple Access Systems

When the actual statistical properties of the CCI-sequence $\{\mu(n)\}$ defined in (1) are fully exploited, we have proved that the updating of the above introduced APP vector $\{\pi(n/n)\}$ can be carried out in a *recursive* fashion on the basis of the following relationships:

$$\pi(n/n-1) = \Phi_\sigma\ \pi(n-1/n-1), \qquad (7)$$

$$\pi^{(i)}(n/n-1) \equiv \left[\ldots P\left(\sigma^{(i)}(n) = \xi_1^{(i)} / r_1^{n-1}\right) \ldots \right]^T = $$

$$= \Phi_\sigma^{(i)}\ \pi^{(i)}(n-1/n-1), n \geq 2, 1 \leq i \leq L,$$

$$\delta_f(n) \equiv \pi N_o P\left(r(n)/\sigma(n) = \xi_f, r_1^{n-1}\right) =$$

$$\equiv \sum_{\xi^{(1)} \in A_\sigma^{(1)}} \cdots \sum_{\xi^{(L)} \in A_\sigma^{(L)}} \exp\left\{ -\frac{1}{N_o} \left\| r(n) - Gh^T \xi_f - \sum_{j=1}^{L} G^{(j)} h^{(j)^T} \xi^{(j)} \right\|^2 \right\} \times$$

$$\times \left(\prod_{j=1}^{L} P\left(\sigma^{(j)}(n) = \xi^{(j)} / r_1^{n-1}\right) \right),$$

$$\Delta(r(n)) \equiv diag\left\{ \delta_1(n), \ldots, \delta_{N_\sigma}(n) \right\}, n \geq 1,$$

$$\pi(n/n) = \frac{\Delta(r(n))\pi(n/n-1)}{\left(\underline{1}_{N_\sigma}\right)^T \Delta(r(n))\pi(n/n-1)},$$

$$\delta_t^{(i)}(n) \equiv \pi N_o P\left(r(n)/\sigma^{(i)}(n) = \xi_t^{(i)}, r_1^{n-1}\right) =$$

$$\equiv \sum_{\xi \in A_\sigma} \sum_{\xi^{(1)} \in A_\sigma^{(1)}} \cdots \sum_{\xi^{(i-1)} \in A_\sigma^{(i-1)}} \sum_{\xi^{(i+1)} \in A_\sigma^{(i+1)}} \cdots \sum_{\xi^{(L)} \in A_\sigma^{(L)}}$$

$$\exp\left\{ -\frac{1}{N_o} \left\| r(n) - G^{(i)} h^{(i)^T} \xi_t^{(i)} - Gh^T \xi - \sum_{\substack{j=1 \\ j \neq i}}^{L} G^{(j)} h^{(j)^T} \xi^{(j)} \right\|^2 \right\} \times$$

$$\times \left(\prod_{\substack{j=1 \\ j \neq i}}^{L} P\left(\sigma^{(j)}(n) = \xi^{(j)} / r_1^{n-1}\right) \right) P\left(\sigma(n) = \xi / r_1^{n-1}\right)$$

$$\Delta^{(i)}(r(n)) \equiv diag\left\{ \delta_1^{(i)}(n), \ldots, \delta_{N_\sigma^{(i)}}^{(i)}(n) \right\},$$

$$\pi^{(i)}(n/n) \equiv \left[\ldots P\left(\sigma^{(i)}(n) = \xi_1^{(i)} / r_1^{n}\right) \ldots \right]^T =$$

$$= \left[\Delta^{(i)}(r(n)) \pi^{(i)}(n/n-1) \right] / \left[\left(\underline{1}_{N_\sigma^{(i)}}\right)^T \Delta^{(i)}(r(n)) \pi^{(i)}(n/n-1) \right],$$

Following the taxonomy introduced in [1], we can state that the optimality (in an SbS-MAP sense) of the above algorithm is achieved by fully exploiting the “discrete random-code-like distribution” of the (L+1) transmitted users’ sequences [1, Sect.III]; thus, according to [1, Sect.III] the resulting computational complexity (per q-ary complex transmitted symbol) of the presented algorithm is proportional to q^{L_T}, where $L_T \equiv L_c + \sum_{i=1}^{L} L_c^{(i)}$. Although we could argue that in actual implementations the above overall computational load can be effectively equidistributed upon (L+1) basic processing units which run *in parallel* and *separately* deliver the (L+1) APP sequences $\{\pi(n/n)\}$ and $\{\pi^{(i)}(n/n)\}$, for large L the requested computational effort could be too large to be supported by the subscribers present in actual LANs. For this reason, starting from some reasonable approximations about the actual statistics of the CCI sequence $\{\mu(n)\}$, in the following Sections we present two reduced-complexity versions of the above algorithm suitable to be implemented at the subscriber side. As a final comment about the algorithm proposed in this Section, we note that the above mentioned modular structure makes its actual implementation appealing at the central offices (base stations) of LANs where also the detection of the L interfering users’ messages of Fig.1 is, indeed, requested [9]; in fact, the generation of the L user messages $\{\hat{a}^{(i)}(n - L_c^{(i)} + 1)\}$, can be *directly* accomplished on the basis of the corresponding APPs vectors $\{\pi^{(i)}(n/n)\}$, via L *separate applications* of the usual MAP decision rule.

4. A Decentralized SbS-MAP Detector for Memoryless CCI Sequences

When the discrete-valued CCI sequence $\{\mu(n)\}$ of eq.(1) can be assumed memoryless (the operative conditions of some emerging non-SS CDMA-type systems [3,4,5] recently proposed in the literature, well match such a kind of assumption), it can be proved that the optimum detection algorithm of the previous Section boils down to the simpler recursive ones below reported:

$$\pi(n/n-1) \equiv \Phi_\sigma\ \pi(n-1/n-1), \qquad (8)$$

$$\Theta_f(n) \equiv \min_{\xi^{(1)} \in A_\sigma^{(1)}} \cdots \min_{\xi^{(L)} \in A_\sigma^{(L)}} \left\{ \left\| r(n) - Gh^T \xi_f - \sum_{i=1}^{L} G^{(i)} h^{(i)^T} \xi^{(i)} \right\|^2 \right\},$$

$$\hat{\Delta}(r(n)) \equiv diag\left\{ \ldots \exp\left(-\frac{\Theta_i(n)}{N_o} \right) \ldots \right\}$$

$$\pi(n/n) \equiv \frac{\left[\hat{\Delta}(r(n))\pi(n/n-1) \right]}{\left[\left(\underline{1}_{N_\sigma}\right)^T \hat{\Delta}(r(n))\pi(n/n-1) \right]}.$$

Since in the above algorithm *only* the APP sequence of the state-chain of the desired channel $\{\pi(n/n)\}$ is computed, according to the taxonomy of [2, Sect.I], this receiver can be qualified as "decentralized". More in detail, the computational load of this algorithm depends on the number L of the interfering users *only* via the L-fold *min*-operations which act on sets of size $q^{(L_T - L_c)}$.

Since the detector presented in this Section fully exploits the knowledge of the (L+1) impulse responses of the channels of Fig.1, it is expected that its performance approaches the one of the optimum detector of Sect.3 when the CCI sequence $\{\mu(n)\}$ is essentially white and the results of Sect.6 support this conclusion.

5. A DECENTRALIZED SBS-MAP DETECTOR FOR COLORED GAUSSIAN CCI SEQUENCES

When the distribution of $\{\mu(n)\}$ conditioned on the observations is Gaussian, the detection algorithm of Sect.3 assumes the following recursive form for PAM transmissions over real baseband ISI channels:

$$\pi(n/n-1) = \Phi_\sigma\, \pi(n-1/n-1), \tag{9}$$

$$\hat{\mu}^{(W)}(n) = \left(K_{\mu r}\right)^T \left(K_{rr}\right)^{-1} r_{n-w}^{n-1},$$

$$\tilde{\delta}_t\ (n) \equiv \exp\left\{ -\frac{\left\| r(n) - Gh^T \xi_t - \hat{\mu}^{(W)}(n) \right\|^2}{\left(2\operatorname{cov}_{\mu\mu}(W) + N_o\right)} \right\},$$

$$\tilde{\Delta}(r(n)) \equiv diag\left\{ \tilde{\delta}_1\ (n), \ldots, \tilde{\delta}_{N_\sigma}\ (n) \right\}$$

$$\pi(n/n) = \frac{\left[\tilde{\Delta}(r(n))\pi(n/n-1)\right]}{\left[\left(\underline{1}_{N_\sigma}\right)^T \tilde{\Delta}(r(n))\pi(n/n-1)\right]}$$

In the above equations, $\hat{\mu}^{(W)}(n)$ indicates the linear MMSE sliding-window Wiener-like estimate of $\mu(n)$ on the basis of the W-windowed observed sub-sequence $r_{n-W}^{n-1} \equiv \left[r(n-1)\ldots r(n-W)\right]^T$, whereas $\operatorname{cov}_{\mu\mu}(W) = \sum_{i=1}^{L}\left(G^{(i)}\right)^2 - \left(K_{\mu r}\right)^T \left(K_{rr}\right)^{-1} K_{\mu r}$ is the MSE of the resulting estimate. Furthermore, the W-variate vector $K_{\mu r}$ gathers the cross-covariances between $\mu(n)$ and r_{n-W}^{n-1} and it is constituted by the lags of the autocorrelation sequence (acs) $\{R_{\mu\mu}(m)\}$ of the CCI-process from m=1 to m=W. Finally, K_{rr} is the usual ($W\times W$) Toeplitz-type covariance matrix built up with the lags of the acs $\{R_{rr}(m)\}$ of the observations $\{r(n)\}$ from m=0 to m=(W-1). Due to the above Gaussian assumption, the computational load of the above decentralized algorithm is obviously *independent* from the number L of interfering users and the corresponding performance is expected to improve when the correlation of the CCI-process increases.

As it is well known [6,9 and references therein], in Gaussian-dominated environments a solution for the CCI-suppression can be directly obtained via a linear MMSE Wiener-like sliding-window filter for the desired data-stream $\{a(n)\}$. More in detail, under the so-called "extended colored Gaussian CCI approximation" of [1, Sect.VI] (see also [6,9]), the (L_c-1)-delayed linear MMSE estimate $\hat{a}(n)$ of the desired data $a(n)$ performed on the basis of the windowed observed vector $r_{n-W}^{n+Lc-1} \equiv \left[r(n+L_c-1)\ldots r(n-W)\right]^T$ can be computed as

$$\hat{a}(n) = G\left[h^T \mid 0_{1\times W}\right]\left(Cov_{rr}\right)^{-1} r_{n-W}^{n+L_c-1}, \tag{10}$$

where the above Cov_{rr} is the usual (W+L_c)-th order Toeplitz-type covariance matrix built up with the lags of the acf $\{R_{rr}(m)\}$ of the observations from m=0 to m=W+L_c-1 (see, for example, [1, eq.(25)]). Afterwards, the MMSE estimate in (10) generates the corresponding hard-detected data $\hat{a}(n)$ via a minimum-Euclidean-distance-based one-shot slicer. However, since the MMSE detector in (10) considers the ISI present in the desired component $\{u(n)\}$ of the observation in (2) as an *additional* Gaussian noise, it is expected that the proposed detection algorithm largely outperforms the standard ones of eq.(10) when the ISI introduced by the MAC system is not negligible (see Sect.6).

6. Numerical Results and Conclusive Remarks

An examination of Figs.2,3 shows that on deeply ISI and CCI impaired environments the performance of the optimum detector of Sect.3 is very good and improves for decreasing SIRs whereas both the conventional single-user and MMSE detectors of eqs.(6),(10) experience crashing phenomena; furthermore, although the CCI sequence of Fig.2,3 is quite colored, the performance of the (simplified) decentralized detector presented in Sect.4 is again acceptable. To this regard, Fig.4 also confirms that the performance of the decentralized detector of Sect.4 closely approaches that of the optimum one of Sect.3 when the overall CCI-sequence is essentially white whereas the conventional receivers of eqs.(6) and (10) again fall short in such an environment.

To test the ultimate effectiveness of the detector proposed in Section 5 and the MMSE conventional one of eq.(10) on Gaussian-dominated environments, we have carried out a set of simulations by directly generating a Gaussian CCI-sequence $\{\mu(n)\}$ with Gaussian-shaped power-density specrtum $P_{\mu\mu}(f)$ given by the usual (normalized) relationship

$$P_{\mu\mu}(f) = \left(\sqrt{\pi}\lambda\right)^{-1} \exp\left[-\left(f/\lambda\right)^2\right], \tag{11}$$

where λ≡-logρ/2π with ρ∈(0,1] being the correlation coefficient of {$\mu(n)$}. The simulation results in Fig.5 confirm that, when the ISI-effects are not negligible the conventional MMSE receiver crashes whereas the one proposed in Section 5 yields to a very good performance.

7. References

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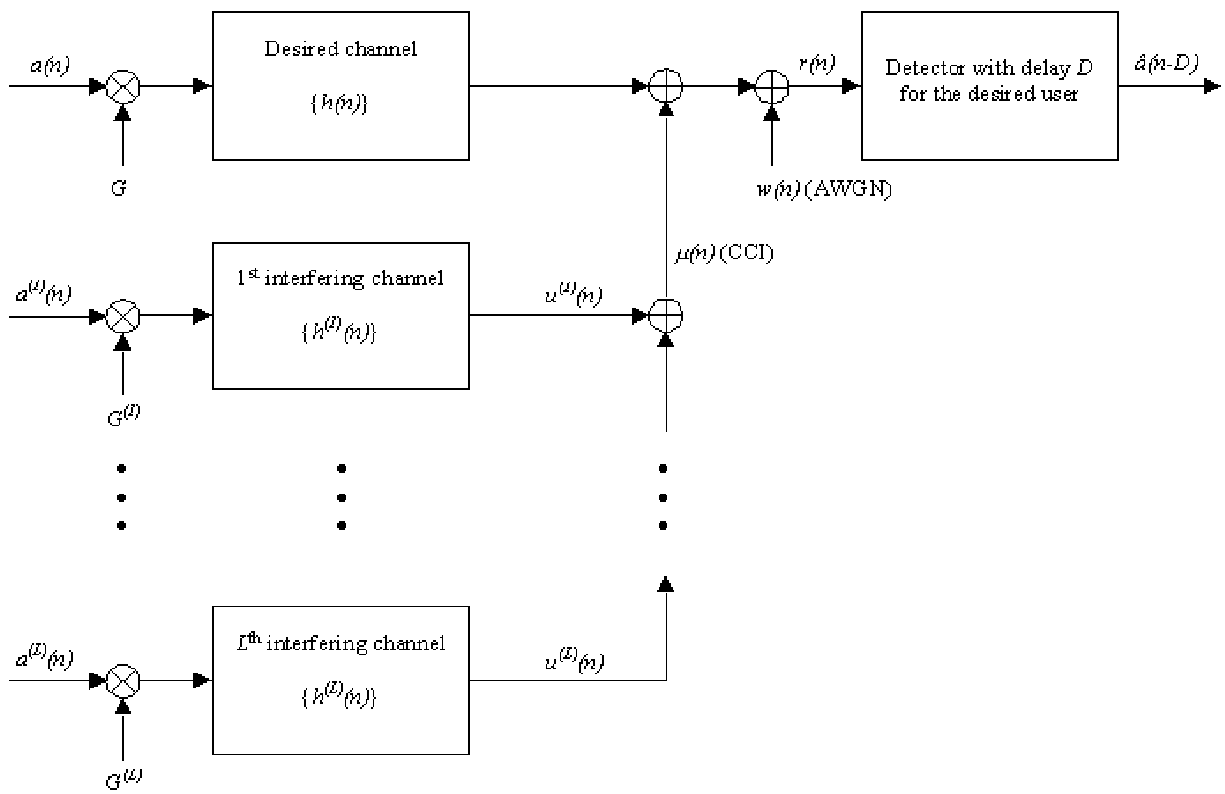

Fig. 1. Baud-rate sampled, baseband non-SS MAC system with ISI and CCI.

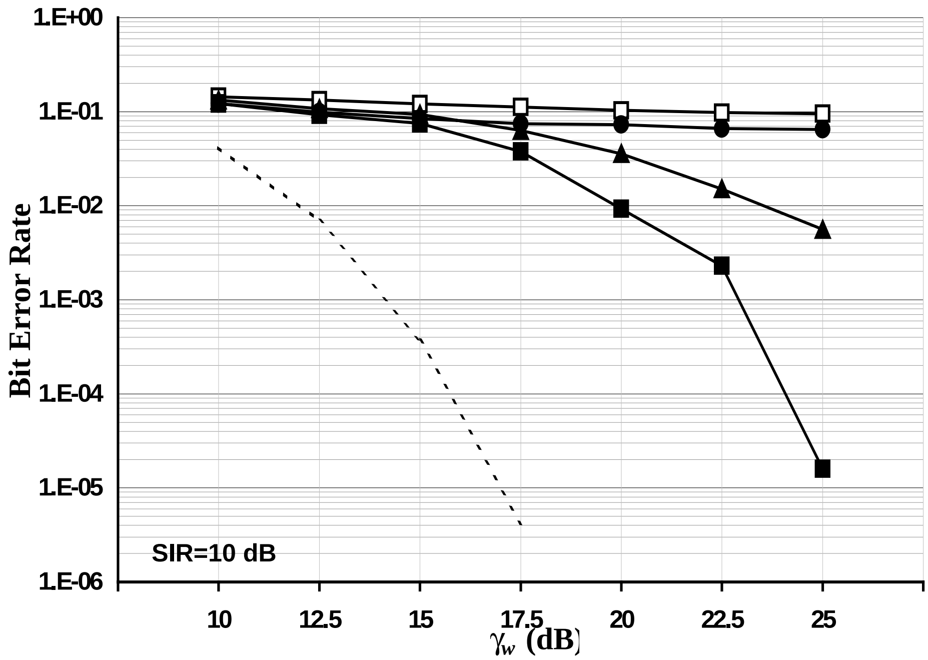

Fig. 2. Performance plots at SIR = 10 dB of the detectors proposed in Section 3 (—■—) and Section 4 (–▲–) and the conventional ones of eq.(6) (–•–) and eq.(10) (—□—) for a BPSK-modulated MAC system with only one interfering (L=1). The impulse responses of the desired and interfering channels are given by h≡[0.447, 0.775, 0.447]^T $h^{(1)}$≡[0.774, 0.627, -0.0854]^T, respectively. As a benchmark, the performance of an SbS-MAP equalizer acting on the desired channel h at an SIR→∞ is also reported (⋯⋯).

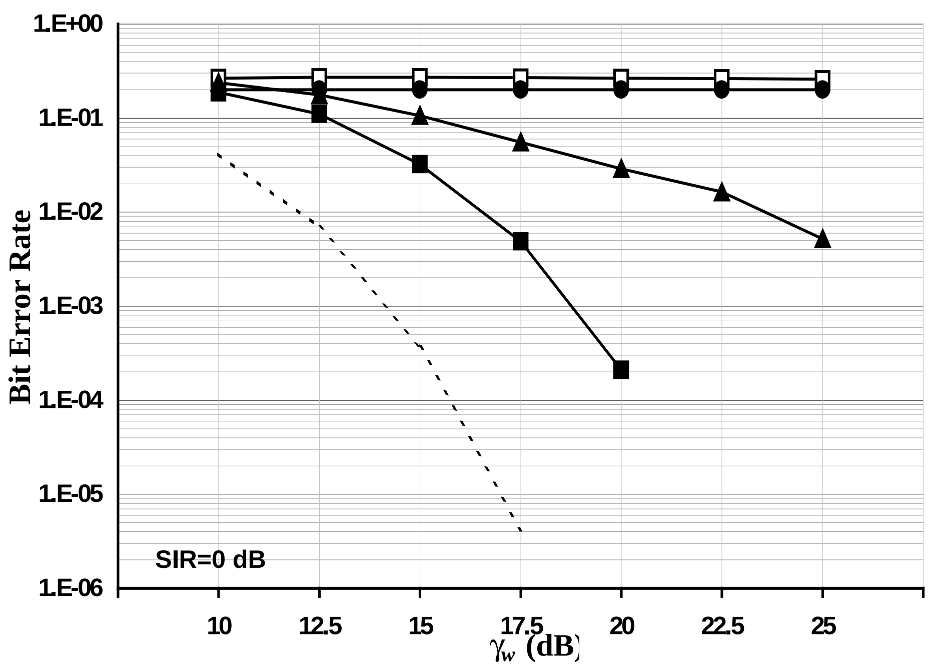

Fig. 3. As in Fig.2 at an SIR = 0 dB.

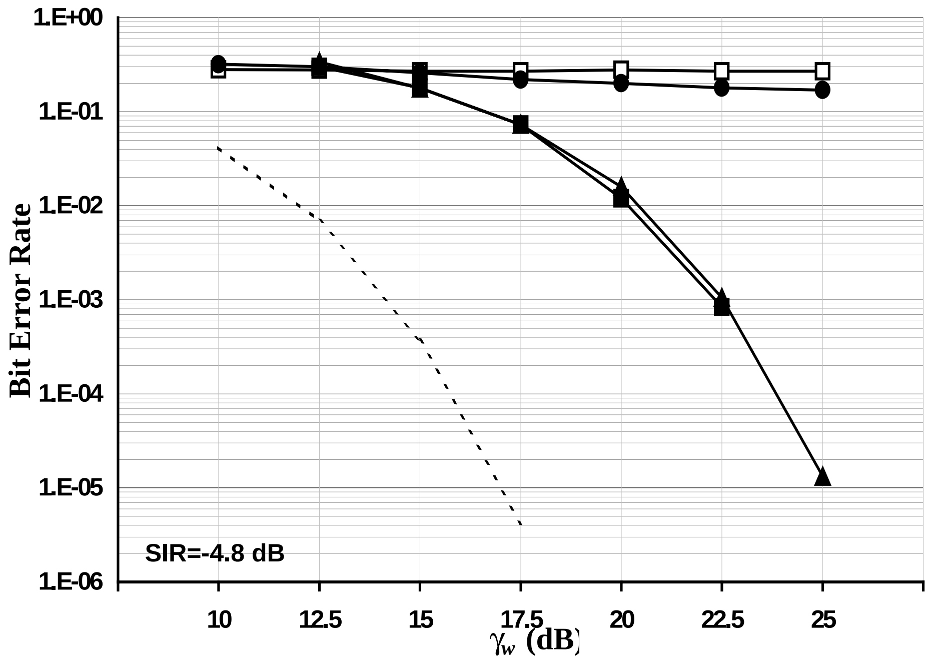

Fig. 4. As in Fig.2 for a BPSK-modulated MAC system with three interferers transmitting all at the same power (i.e., SIR = - 4.8 dB). The impulse responses of the desired and interfering channels are given respectively by: h≡[0.447, 0.775, 0.447]^T, '$h^{(1)}$≡0.5[1, -1, 1, -1]^T, $h^{(2)}$≡0.5[1, 1, -1, -1]^T, $h^{(3)}$≡0.5[1, -1, -1, 1]^T.

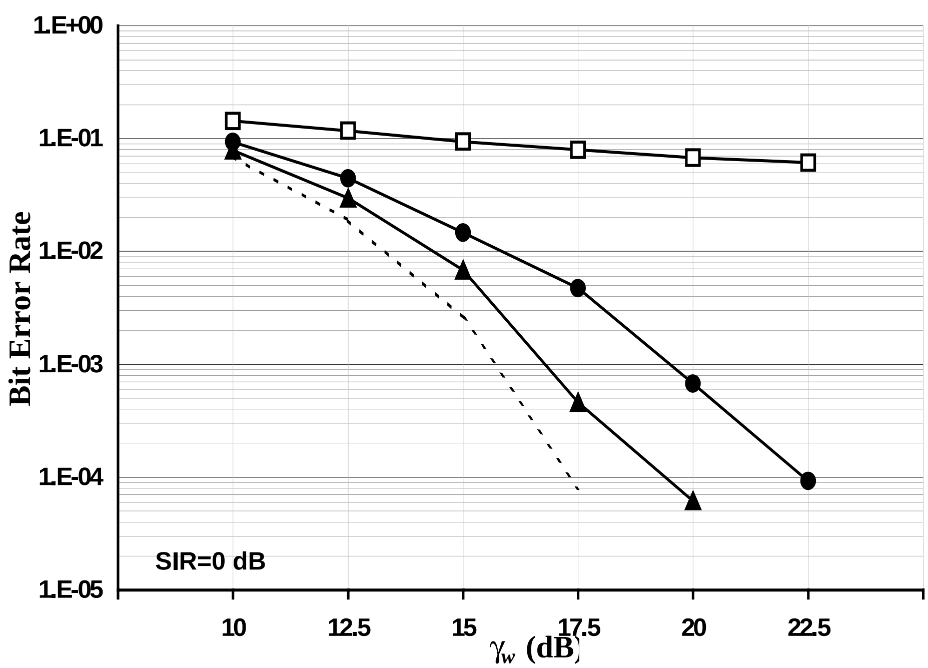

Fig. 5. Performance plots at SIR γ_I=0 dB of the detector proposed in Section 5 (–•– for W=6 and –▲– for W=10) and the conventional one of eq.(10) (—□— at W=10) for the colored Gaussian-shaped CCI sequence of eq.(11) with $\lambda=10^{-3}$. The impulse-response of the desired channel is h≡0.5[1, -1, 1, -1]^T. The corresponding performance of an SbS-MAP equalizer at an SIR→∞ is marked as (┈┈┈).