CO-CHANNEL INTERFERENCE CANCELLING RECEIVER FOR TDMA MOBILE SYSTEMS

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Abstract- **In this paper a method for co-channel interference cancellation in TDMA mobile systems exploiting the characteristics of mobile channels is proposed. The independently fading multipath channels provide a distinct waveform coding on each of the co-channel signals, which is a basis for signal separation in receivers. This enables the use of joint detection methods in receivers provided that accurate channel estimates can be obtained for all the co-channels. In this paper a joint detection and channel estimation algorithm for multiple co-channel signals are derived. The performance of the receiver is verified by simulations with the GSM system assuming that the strongest interferer is cancelled.**

I. INTRODUCTION

For the future development of mobile cellular systems the availability of the radio spectrum will be one of the key problems. In narrowband mobile systems the co-channel interference (CCI) problem is one of the major factors limiting the system capacity, although the cellular capacity could still be improved by using the well-known cell-splitting and power reduction technique. Another possibility is to follow the rapid development of digital signal processing techniques and make use of the rather complex interference cancellation algorithms in receivers. The removal of CCI enables higher frequency re-use in a network. Alternatively, coverage or radio transmission quality can be improved.

In the current TDMA mobile receivers, the interfering co-channel signals are usually approximated as a random additive white Gaussian noise process. However, the fact that CCI is deterministic in nature implies that we should at least partially be able remove its influence. Particularly in TDMA mobile systems, it is often valid to assume that one or two interferers dominate the others. This is mainly due to the asymmetric positions of receivers with regard to their interferers and independent shadows in the interferers' propagation paths. Evidently in this type of situation it is most profitable to concentrate on the cancellation of the strongest interferers, and thereby simplify receiver algorithm.

Interference cancellation (IC) and multi-user detection (MUD) methods have gained significant interest in research works for CDMA cellular applications. For narrowband TDMA systems they are relatively new ideas although special attention has already been paid on this subject in some papers [1,2,3,4]. Application of IC/MUD techniques to narrowband TDMA transmission is basically a more difficult task than in CDMA due to the fact that signal separation is not optimised by the transmitted waveforms as in CDMA. Nevertheless, signal separation is also possible in narrowband systems due to the waveform coding provided by radio channel itself. Independent signal fading, multipath propagation and received powers are factors which make co-channel signals different enough to enable signal separation in receivers.

The most powerful narrowband IC techniques rely on the joint detection (JD) of co-channel signals in which the transmitted sequences are detected by the MLSE principle [3,4,5]. A fundamental requirement for successful joint detection is that the possible signal states do not severely overlap at the channel output. As discussed above, mobile channels will likely guarantee this condition. Furthermore, the IC-receiver should be able to find the locations of the signal states and their labels. This estimation problem can be straightforwardly solved by performing joint channel estimation for multiple co-channels with the aid of synchronously transmitted training sequences.

The organisation of this paper is following. First we describe the system model and formulate the problem in mathematical terms. Then we present the IC-receiver algorithm including a channel estimation and detection method for multiple co-channel signals. After that we demonstrate by simulations its performance using the GSM transmission parameters. In the simulation model, only the dominant interfering co-channel signal is jointly estimated with the desired signal. Finally, the conclusions are drawn.

II. FORMULATION OF THE PROBLEM

The discrete-time model in the complex low-pass equivalent form for a co-channel communications system is depicted in Fig. 1. It consists of N co-channel signals each having independent time-variant complex channel impulse response $\mathbf{h}_{L,n} = \left(h_{0,n}, h_{1,n}, \ldots, h_{L,n}\right)$ where L is the length of the channel memory in symbols. Without loss of generality we assume 2-

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PAM signalling, so that the transmitted symbols $a_{k,n} \in [-1,+1]$ form the transmitted symbol sequences $\mathbf{a}_{K,n} = (a_{1,n},\ a_{2,n}, \dots a_{K,n})$ of length K in each N channels. The vector $\mathbf{r}_K = (r_1,\ r_2, \dots,\ r_K)$ is the received signal sequence and $\mathbf{n}_K$ is a sequence of independent white Gaussian noise samples. The model is simplified in the sense that it assumes that the length of the channel memory L to be finite and equal for all the channels.

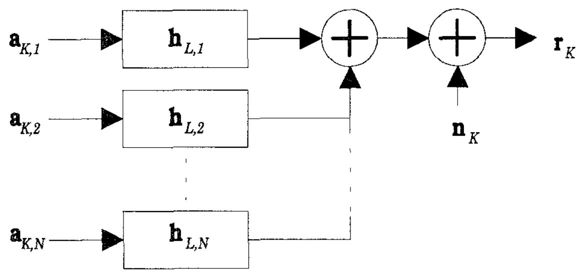

Figure 1 Co-channel communications system with N co-channel signals

More accurately, the received signal r_k sampled once per symbol can be written as

$$r_k = \sum_{n=1}^{N}\sum_{l=0}^{L} h_{l,n} a_{k-l,n} + n_k . \qquad (1)$$

The problem is now to detect the N transmitted data sequences $\mathbf{a}_{K,n}$ from $\mathbf{r}_K$. This can be accomplished with high probability provided that the signal states at channel output do not fall on the top of each other and additive noise power is low enough.

In mobile channels the co-channel signals are summed up in random phases and amplitudes, thus the probability of signal state overlap is a very small. In addition, using the MLSE principle in this multichannel detection problem, the performance loss is reasonable in comparison with a single channel case. It turns out that the estimation of the channel parameters in this multichannel case is a more severe problem than the detection of multiple signals itself. This will be demonstrated by simulations in Chapter VI.

III. Joint Detection

It is well-known that the optimum detection algorithm in the presence of Intersymbol Interference (ISI) and white Gaussian noise is MLSE which can be implemented in a recursive manner by the Viterbi algorithm [6]. W. van Etten [5] has shown that the Viterbi algorithm can be straigthforwardly extended to the detection of multiple co-channel signals with simultaneous ISI compensation. He named the algorithm as the vector Viterbi algorithm. Recently, Giridhar *et. al* [3,4] have investigated MLSE for co-channel interference cancellation in static ISI channels and assuming that the channel parameters are known. By Giridhar, the algorithm is called Joint MLSE (JMLSE). By using standard trellis search techniques it is able to find the most likely transmitted symbol sequences out of all possible sequences using the maximum likelihood criterion

$$\max_{\substack{\mathbf{a}_{K,n}\\ n\in[1,N]}} \left[p\left(\mathbf{r}_K \middle| \mathbf{a}_{K,1}, \mathbf{a}_{K,2}, \dots, \mathbf{a}_{K,N}\right)\right], \qquad (2)$$

where $p\left(\mathbf{r}_K \middle| \mathbf{a}_{K,1}, \mathbf{a}_{K,2}, \dots, \mathbf{a}_{K,N}\right)$ is the joint probability density function of random variables $\mathbf{r}_K$ conditioned on the transmitted sequences $\mathbf{a}_{K,n}$. The most likely transmitted symbol sequences are those that maximise the quantity above. Assuming independent noise samples we can express Eq. (2) as

$$\max_{\substack{a_{k,n}\\ n\in[1,N]}} \left[\prod_{k=1}^{K} p\left(r_k \middle| \mathbf{a}_{L+1,1}, \mathbf{a}_{L+1,2}, \dots, \mathbf{a}_{L+1,N}\right)\right] , \qquad (3)$$

where the vector $\mathbf{a}_{L+1,n}$ contains the L+1 previously transmitted symbols in the nth channel, i.e., $\mathbf{a}_{L+1,n} = (a_{k,n}, a_{k-1,n}, \dots, a_{k-L,n})$.

Furthermore, assuming that the noise is Gaussian with zero mean and variance σ^2, the conditional probability density function in Eq. (3) is given as

$$p\left(r_k \middle| \mathbf{a}_{L+1,1}, \dots, \mathbf{a}_{L+1,N}\right) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{1}{2\sigma^2} \left| r_k - \sum_{n=1}^{N}\sum_{l=0}^{L} h_{l,n} a_{k-l,n} \right|^2 \right) \qquad (4)$$

Given this the original criterion in Eq. (2) can be converted into a more convenient loglikelihood criterion formulated as

$$\min_{\substack{\mathbf{a}_{K,n}\\ n\in[1,N]}} \left[\sum_{k=1}^{K} \left| r_k - \sum_{n=1}^{N}\sum_{l=0}^{L} h_{l,n} a_{k-l,n} \right|^2 \right]. \qquad (5)$$

The equation returns the minimum sum of Euclidean distances over all possible sequences.

Since the use of the Viterbi algorithm requires a recursive formulation of the likelihood function, we write the final form of the JMLSE path metrics as

$$J_k(\mathbf{a}_{k,n}) = J_{k-1}(\mathbf{a}_{k-1,n}) + \left| r_k - \sum_{n=1}^{N}\sum_{l=0}^{L} h_{l,n} a_{k-l,n} \right|^2 \qquad (6)$$

where the term $J_{k-1}(\mathbf{a}_{k-1,n})$, $n = 1,2,\dots,N$ presents the survivor path metric at the previous stage in the trellis. In fact, the path metrics of the conventional Viterbi detector is similar to Eq. (6) except n can only have the value 1. In other words, the difference is that in every symbol period JMLSE weights the symbols $(a_{k,1}, a_{k,2}, \dots, a_{k,N})$ jointly instead of $a_{k,1}$ alone.

The number of the states in the JMLSE trellis is 2^{NL}. Due to computational limitations, we cannot allow the product NL to be very high. This obviously limits the number of co-channel signals we are able jointly detect or alternatively the multipath spread we can tolerate. As already mentioned, in TDMA mobile systems the number of dominant interferers can be small suggesting that the receiver complexity can be reduced by cancelling only those ones.

IV. Channel Estimation

In this chapter we derive a joint channel estimation method of multiple co-channel signals for the GSM type of systems, in which training sequence is transmitted in every transmission burst. The formulation is identical to that presented in [7] for CDMA uplink channel estimation.

The joint channel estimation is necessary because of the cross-correlation disturbance between the co-channel signals simultaneously present in the channel. In the following we assume that the training sequences in the co-channels are synchronous so that the effects of cross-correlation can be removed using the tools of the linear algebra.

Suppose there are N synchronous co-channels, i.e., the primary user and N-1 interferers each having a different channel. Denote the N radio channels as

$$\mathbf{h}_{L,n} = (h_{0,n}, h_{1,n}, \ldots, h_{L,n})^T, \quad n = 1, 2, \ldots, N,$$

each of length (L+1) with complex channel tap weights. Collect the channel impulse responses into the vector $\mathbf{h}$ as follows

$$\mathbf{h} = (\mathbf{h}_{L,1}^T, \mathbf{h}_{L,2}^T, \ldots, \mathbf{h}_{L,N}^T)^T.$$

The number of parameters above is thus $N \times (L+1)$. The training sequence of the nth channel consisting of the preamble and midamble codes is denoted by

$$\mathbf{m}_n = (m_{0,n}, m_{1,n}, \ldots, m_{P+L-1,n})^T, \quad n = 1, 2, \ldots N,$$

with $L+P$ elements $m_{p,n} \in [-1,1]$, where L is the length of the preamble code equal to the length of channel memory and P is the length of the midamble code. The first L bits are the preamble code bits and the next P bits are midamble code bits.

The received signal corresponding to the midamble code bits is then

$$\mathbf{y} = \mathbf{M}\mathbf{h} + \mathbf{n} \tag{7}$$

where $\mathbf{n}$ represents Gaussian noise samples with the covariance matrix $\mathbf{R}$, and the matrix $\mathbf{M} = (\mathbf{M}_1, \mathbf{M}_2, \ldots, \mathbf{M}_N)$ includes the transmitted training sequences organised to the matrices $\mathbf{M}_n$ n=1,2...,N as

$$\mathbf{M}_n = \begin{bmatrix} m_{L,n} & \cdots & m_{1,n} & m_{0,n} \\ m_{L+1,n} & \cdots & m_{2,n} & m_{1,n} \\ \vdots & & \vdots & \vdots \\ m_{P+L-1,n} & \cdots & m_{P,n} & m_{P-1,n} \end{bmatrix}.$$

The maximum likelihood channel estimate is given by

$$\hat{\mathbf{h}}_{ML} = (\mathbf{M}^H \mathbf{R}^{-1} \mathbf{M})^{-1} \mathbf{M}^H \mathbf{R}^{-1} \mathbf{y}, \tag{8}$$

and assuming that the noise is white Eq. (8) reduces to

$$\hat{\mathbf{h}}_{ML} = (\mathbf{M}^H \mathbf{M})^{-1} \mathbf{M}^H \mathbf{y}. \tag{9}$$

As a conclusion, the result is equivalent to the conventional channel estimator with N equal to 1. We can see that the noise variance is increased as if the correlation matrix is $\mathbf{M}^H\mathbf{M}$ is not ideal causing degradation in the receiver performance.

V. SIMULATION MODEL

In the simulations we considered the case where the dominant interferer alone was jointly detected with the desired signal (see Fig. 2). This kind of test configuration is especially interesting for TDMA mobile systems for which it is often valid to assume that a dominant interferer exists and the others have significantly less power. By neglecting the less important interferers, a huge computational savings can be achieved, but still a significant performance gain is earned.

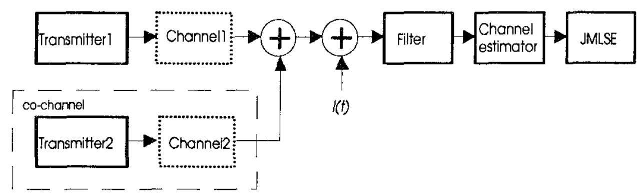

Figure 2 Simulation configuration, I(t) is the sum of the non-detected co-channel interferers.

The simulations were run using the standard GSM transmission system parameters in conjunction with the COST207 multipath channel models [8]. The co-channel signals are independently fading. We neglect the effect of the receiver noise by assuming the sum power of the non-detected interferers $I(t)$ is much higher than the noise power. The detector part performs the algorithm described in Chapter III with N equal to 2.

The channel estimator estimates five channel taps (L=4) from the both channels. Thus, the conventional GSM Viterbi receiver with 16 states expands to 256 states for JMLSE. The training sequence pair (0,2) from the GSM set [8] was confirmed to perform the best from the GSM sequences, therefore it is consistently used throughout the paper.

VI. SIMULATION RESULTS

In this chapter, we compare the performance of the IC-receiver with that of the conventional receiver. In addition to the channel estimation algorithm, which we call the TS channel estimate, is evaluated against the clean (interference free) channel estimate in terms of the receiver performance. In all cases, the performance is evaluated at the detector output without channel coding.

The results in Fig. 3 are obtained by jointly detecting the desired and one interfering signal as function of the signal-to-interference ratio (SIR) in the Typical Urban 3 km/h channel (TU3). Note that there is no other interferers or even noise present in the transmission media. We can see the superiority of JMLSE with the TS-channel estimation over the conventional receiver with the gain around 20 dB throughout the curve. Still, the performance is getting worse as the interference power increases. This can be explained by the residual ISI from the interfering channel that is increasing along with the interference power. More accurately, the residual ISI powers P_{1t} and P_{2t} of the desired and interfering signals (see Fig. 4) count to the signal to residual ISI ratio according to the following formula:

$$\frac{\textit{Signal Power}}{\textit{Residual ISI}} = \frac{P_1}{P_{1t} + P_{2t}} \qquad (10)$$

where P_1 is the signal energy of the desired signal fed into the detector (see Fig. 4). As if P_{2t} increases with respect to P_1 and P_{1t} we can easily understand the degradation in performance.

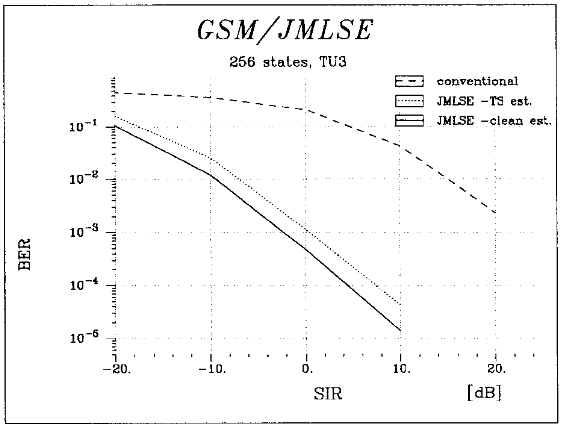

Figure 3 JMLSE (N=2) with both the clean and TS channel estimates against the conventional receiver performance with one interferer which is jointly detected. The channel model is Typical Urban 3 km/h.

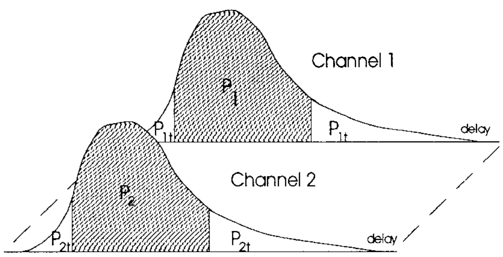

Figure 4 The channel impulse responses of two co-channels. The hatched areas describe the part fed into the detector and the white area the residual part.

From Fig. 3 we can see that the loss resulting from the channel estimation is about 3 dB in comparison with the clean estimate. By thinking the residual ISI as additive noise, we can find at least two reasons for the deterioration. Firstly, the residual ISI components degrades the channel estimation reliability by introducing an additive noise like process. Secondly, this noise variance is enhanced during the channel estimation process due to the non-ideal correlation properties of the training sequences.

In Fig. 5 we show the receiver performance as a function of the total SIR with two interferers from which only the other (I1) is jointly detected. The channel type is TU3. In the figure, multiple curves are drawn for the different ratios of the detected interferer (I1) and non-detected interferer (I2). For example, if the detected interferer is 5 dB higher than the non-detected interferer, the gain is about 3 dB but for 20 dB the gain is already from 15 to 16 dB. It is important to notify that the performance never gets worse than that of the conventional receiver even if the ratio is negative.

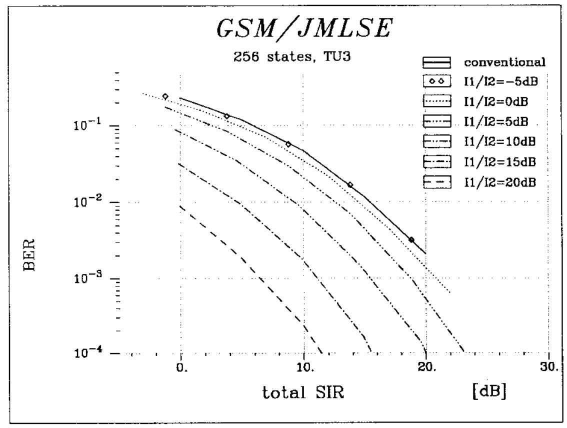

Figure 5 JMLSE (N=2) with the TS channel estimation against the conventional receiver with two interferers from which the I1 is detected. The channel model is Typical Urban 3 km/h.

Fig. 6 draws the performance as a function of the signal to non-detected interferer ratio (SIR2) in the TU3 channel. The average power of the desired signal and the detected interferer is kept the same, i.e. SIR1=0 dB. In the same figure, the conventional receiver performance is plotted with SIR1=∞. By plotting the curves in this way we can demonstrate the trade-off between the joint detection of the two signals and the receiver sensitivity with regard to SIR2.

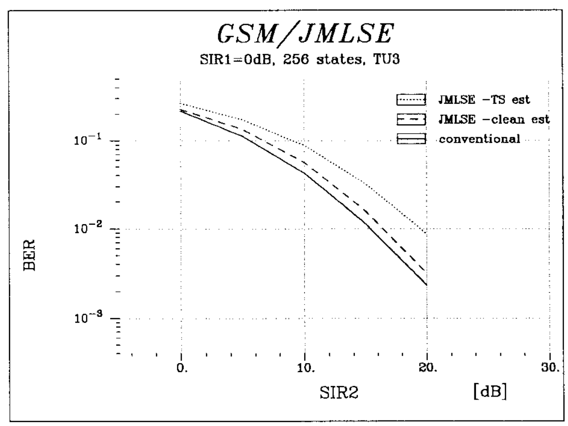

Figure 6 JMLSE (N=2) with both the clean and TS channel estimates against the conventional receiver as a function of the second interferer not detected in the receiver in Typical Urban 3 km/h channel.

Hence, we can state that the cost of removing one interferer equally strong with the desired signal results to 3-4.5 dB worse receiver sensitivity in comparison with conventional receiver. The major contributor to this degradation is the channel estimator which adds 2-3 dB extra loss compared to the clean estimate.

In Fig. 7 we show results in the COST207 Rural Area 3 km/h channel which includes a strong LOS component in its power profile. The test configuration corresponds to that of Fig. 5. We can see that the IC-receiver works well also in this channel type and the potential gain is almost as much as in TU channel. The independence of signal phases and amplitudes seem to guarantee the signal separation also in this case.

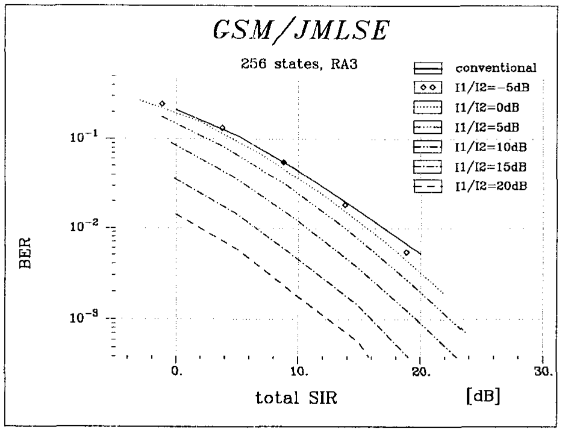

Figure 7 JMLSE (N=2) with the TS channel estimation against the conventional receiver with two interferers from which the I1 is detected. The channel model is Rural Area 3 km/h.

VII. Discussion

In the simulations, we have assumed an ideal synchronisation of co-channel bursts. We accepted this limitation to be able provide simulation results with a true channel estimation algorithm which could also be used in a real system. Especially, if the base stations are synchronised and they are fairly close to each other, the assumption of the burst synchronism is reasonable. The proposed channel estimation algorithm is not sensitive to small timing errors of a few symbols. The problem of frequency offset between the jointly detected co-channel signals is not severe either and it can be further alleviated by integrating a standard channel phase tracking algorithm into the detector.

We used 256 states in the JMLSE trellis in all simulations. This number was chosen to be consistent with the conventional 16-state Viterbi detector having memory of four symbols. However, only a minor loss can be found by using 64 trellis states in TU channel and even 16 trellis states could be enough for RA channel. Alternatively, the number of cancelled interferers could be increased in less severe ISI channels. In static channels, the independence of co-channel transmitters with different transmission powers, path losses and signal phases will likely guarantee the signal separation.

The proposed IC-receiver seems technically very interesting for the microcellular and urban macrocellular environment where high capacity is required. In small cells the BS synchronisation can be achieved more easily due to the shorter BS distances. Moreover, the simulations in RA channel showed that LOS situation typical for microcells was not a problem for the IC-receiver.

IIX. Conclusions

The interference cancelling receiver with joint detection and channel estimation algorithms was shown by simulations to be able to utilise the waveform coding provided by the fading multipath channels for alleviating the co-channel interference problem. The gain of jointly detecting the strongest co-channel interferer was shown to be 15-16 dB in the TU3 channel compared to the conventional receiver provided that the sum power of other interferers is 20 dB lower than the strongest one. However, the gain is gradually decreasing as if the other interferers are getting closer to the strongest one. Nevertheless in TDMA mobile systems the existence of a dominant interferer is probable. Another way of looking at the gain is to investigate the receiver sensitivity loss against the non-detected interferers. From this viewpoint, the cancellation of one interferer equally strong with the desired signal requires 3.0 to 4.5 dB more power. The sensitivity loss stems mainly from channel estimation process which suffers from the noise enhancement due the non-ideal training sequence cross-correlation properties. In addition, the residual ISI has an major influence, especially when the interferer is strong. A study of the potential gains for cellular networks will be presented in [9].

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