Distributed multiuser detection for the TDMA cellular uplink

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A method for performing multiuser detection using observations from multiple base stations is proposed. Log-likelihood ratio estimates of the data are calculated at each base station and combined to form the final decision statistic. The proposed architecture is applied to the time division multiple access (TDMA) cellular uplink, and it is shown that heavily overloaded systems can perform remarkably well.

Introduction: The performance and capacity of cellular systems is limited by multiple access interference (MAI) and the related near-far effect. The detrimental effects of MAI can be mitigated by multiuser detection (MUD) [1]. Although MUD research has focused on direct sequence code division multiple access (DS-CDMA), recent studies have shown that it is also suitable for time division multiple access (TDMA) systems [2, 3]. In DS-CDMA cellular networks, the performance is dominated by MAI from within the same cell (intracell interference). In contrast, the performance of TDMA cellular networks is dominated by MAI from nearby cells (intercell interference).

Since the co-channel interference in TDMA systems comes from other cells, considerable improvements can be made by combining information from multiple base stations. In [4], it is shown that the performance can be improved by performing MUD at each base station in a cluster of M cells, and then combining the MUD outputs. The MUD algorithm estimates the *a posteriori* log-likelihood ratio (LLR) for each user, and the final decision statistic is obtained by adding together the LLRs produced by the M base stations. In this Letter, we show that the distributed multiuser detection technique initially presented in [4] can be used to overload the TDMA cellular uplink with more than one co-channel user per cell.

System model: We consider a multiaccess communications network composed of K transmitters and M receivers. In baseband notation, the output of transmitter k, $1 \leq k \leq K$, is

$$s_k(t) = \sum_{n=0}^{N-1} v_{k,n} g(t - nT_s) \qquad (1)$$

where $\{v_{k,n}\}$, $0 \leq n \leq N - 1$, is a sequence of N binary phase shift keying (BPSK) modulated symbols (i.e. $v_{k,n} \in \{-1, 1\}$), $g(t)$ is a pulse shape with energy E_b, and T_s is the symbol period. The impulse response of the channel between transmitter k and receiver m is $h_{m,k}(t) = c_{m,k}(t) \delta(t - \tau_{m,k})$, where $c_{m,k}(t)$ is a complex fading process and $\tau_{m,k}$ is the propagation delay, assumed to be less than one symbol period (i.e. $0 \leq \tau_{m,k} < T_s$). For ease of exposition, we assume a frequency-flat channel, but the results can be easily extended to incorporate the frequency-selective case. The signal arriving at receiver m is

$$y_m(t) = \sum_{k=1}^{K} s_k(t) * h_{m,k}(t) + n_m(t)$$
$$= \sum_{k=1}^{K} c_{m,k}(t) s_k(t - \tau_{m,k}) + n_m(t) \qquad (2)$$

where $n_m(t)$ is a complex white Gaussian noise process with two-sided power spectral density $N_0/2$.

At each base station, the received signal is passed through a bank of K matched filters, each matched to and synchronised with a particular user. The matched filter output for user k is

$$y_{m,k,n} = \int_0^{T_s} g(t) y_m(t + \tau_{m,k} + nT_s) dt \qquad (3)$$

In a conventional system, which uses neither macrodiversity combining nor multiuser detection, the bit estimates are $= \hat{v}_{k,n} = sgn\{y_{m',k,n}\}$, where m' is the base station that receives the signal from user k with the highest signal-to-interference-and-noise ratio (SINR). For the proposed system, the outputs of the K matched filters at receiver m are placed into a vector in 'round-robin' fashion:

$$\mathbf{y}^{(m)} = \left[y_{m,1,0} \; y_{m,2,0} \; \cdots \; y_{m,K,0} \; y_{m,1,1} \; \cdots \; y_{m,K,N-1}\right]^T \qquad (4)$$

The vector $\mathbf{y}^{(m)}$ is processed by a soft-output MUD, which produces the LLR:

$$\Lambda_i^{(m)} = \ln \frac{P[v_i = +1 | \mathbf{y}^{(m)}]}{P[v_i = -1 | \mathbf{y}^{(m)}]} \qquad (5)$$

where v contains symbols with indices corresponding to the ordering of eqn. 4. Eqn. 5 can be computed using the MAP algorithm [5], implemented here using the log-MAP method [6] due to its robustness and reduced complexity. Note that the soft-output MAP algorithm replaces the Viterbi algorithm used in the maximum likelihood sequence estimate (MLSE) formulation of the MUD in [1].

Now, we let Λ be the LLR given the observations from all M receivers:

$$\Lambda_i^{(m)} = \ln \frac{P[v_i = +1 | \mathbf{y}^{(1)}, ..., \mathbf{y}^{(M)}]}{P[v_i = -1 | \mathbf{y}^{(1)}, ..., \mathbf{y}^{(M)}]} \qquad (6)$$

Assuming that the observations at the M receivers are independent (which is true for sufficient receiver spacings),

$$\Lambda_i = \ln \frac{\prod_{m=1}^{M} P[v_i = +1 | \mathbf{y}^{(m)}]}{\prod_{m=1}^{M} P[v_i = -1 | \mathbf{y}^{(m)}]}$$
$$= \sum_{m=1}^{M} \ln \frac{P[v_i = +1 | \mathbf{y}^{(m)}]}{P[v_i = -1 | \mathbf{y}^{(m)}]}$$
$$= \sum_{m=1}^{M} \Lambda_i^{(m)} \qquad (7)$$

Thus, the overall LLR is merely the sum of the LLRs from the M receivers. In the proposed receiver, the final decision is made from the sum of the LLRs, i.e. $\hat{v}_i = sgn\{\Lambda_i\}$.

Simulation results: The potential of the proposed distributed multiuser detection technique is best illustrated by simulation. We consider a TDMA cellular network that uses 120° sectorised antennas at the base stations. In such a system, the signal $y_m(t)$ at each base station is dominated by three users: the desired user plus the two interferers originating from the first tier of co-channel cells. Instead of representing the network topology with base stations at the centre of the cells, we represent it with base stations at three equally spaced corners of each hexagonal cell.
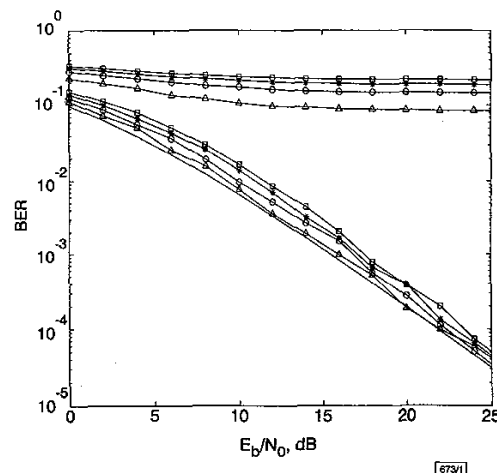

Fig. 1 *BER against E_b/N_o for conventional detection and distributed multiuser detection*

☐ $K = 9$
✳ $K = 7$
○ $K = 5$
△ $K = 3$
– – – – Conventional detection
——— Distributed MUD
·········· Single-user bound

In the simulation study, we considered a network with $M = 3$ receivers located at equally spaced corners of a hexagonal cell, and a variable number of transmitters, $1 \le K \le 9$, randomly placed within the cell with uniform distribution. A fully-interleaved Rayleigh flat-fading channel is assumed (i.e. samples of $|c_{m,k}(t)|$ are i.i.d. Rayleigh distributed). Each user transmits frames of $N = 100$ BPSK symbols, and the signals arrive asynchronously at each base station with relative delay $\tau_{m,k} = (k - 1)/(KT_s)$. A more realistic simulation would have the delays uniformly distributed over $[0, T_s)$ with a new set of delays chosen after each Monte Carlo trial. However, our computational resources prevented us from constantly recomputing the delay profile. After each Monte Carlo trial (consisting of one frame from each user), the mobiles are randomly repositioned within the cell. An exponential path loss is assumed, with path loss exponent $n_e = 3$ [7]. The mobiles are power controlled so that the average SNR at the base station closest to the mobile equals E_b/N_o. For each data point, 100 independent error events were logged.

The bit error rate (BER) for conventional reception and distributed multiuser detection is shown against E_b/N_o for various values of K in Fig. 1. The upper curves (dashed-lines) represent the performance using conventional reception, which does not combine receiver outputs or perform multiuser detection. The lower curves (solid lines) show the performance using the proposed technique. The dotted line shows the theoretical performance of a single-user system with macrodiversity combining, derived using the techniques of [8]. Owing to MAI, the performance of the conventional technique quickly reaches an error floor and is unacceptable for $K > 1$. However, the performance using the proposed distributed MUD technique is greatly improved. The performance degrades with an increasing number of users, but remains within a few decibels of the single-user bound. These results indicate that, by using the proposed system, it may be possible to overload a TDMA system with more than one co-channel user per cell.

Discussion: A technique for distributed multiuser detection has been presented and applied to the TDMA cellular uplink, resulting in a significant increase in system capacity. To fully exploit the proposed architecture, the critical issues of estimation and synchronisation must be addressed. For coded systems, the principle of iterative decoding can be used to greatly improve performance by feeding LLRs derived by a set of channel decoders back to the multiuser detectors [9].

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Hybrid image/ray-shooting UHF radio propagation predictor for populated indoor environments

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A novel model for indoor wireless communication, based on a dual image and ray-shooting approach, is presented. The model, capable of improved site-specific indoor propagation prediction, considers multiple human bodies moving within the environment. In a modern office at 2.45GHz, the combined effect of pedestrian traffic and a moving receiver causes rapid temporal fading of up to 30dB.

Introduction: A new approach for site-specific indoor propagation channel modelling is presented, where moving human bodies are introduced as an additional form of obstruction. At ultrahigh frequency (UHF) and above, the movement of people within the indoor environment leads to strong variations in the propagation channel: critical fading may occur in otherwise adequate systems as contributory ray-paths are created or blocked. Ray-tracing has been used extensively to predict indoor radio propagation [1, 2], but there have been no previous attempts to deterministically include human body obstruction within these models, despite recent interest in statistical models [3]. In addition, the influence of the human body becomes a limiting factor in the performance of any radio system when the antennas are placed in close proximity to it, for example in the case of a personal digital assistant (PDA).

Human body model: In our ray-tracing simulations at 2.45GHz, the body was approximated as a homogeneous, lossy dielectric cylinder 1.8m tall and 0.3m in diameter with the electromagnetic characteristics of muscle ($\varepsilon p_r = 53.5$, $\sigma = 1.81\,Sm^{-1}$). The theoretical wave penetration depth is extremely low (3.75mm) and incident waves cannot fully penetrate through the body. Waves incident on the body surface, however, are subject to relatively high reflection coefficients at this frequency: for vertical polarisation the range is ~0.775–0.995, depending on the incidence angle. Consequently, it is essential to consider contributions from off-body reflections in indoor propagation scenarios where there is movement of personnel or 'pedestrian traffic'. By implementing a uniform geometric theory of diffraction (GTD) solution [4], waves diffracted around the body were also included in the model. Since their contribution is generally small, these 'creeping' waves were taken into account only where the body in question was obstructing the direct ray to a receiver placed in the deep shadow region cast by the obstruction. Antenna-body interaction effects at a personal mobile terminal (with the antenna very close to the body) can be included by using an appropriately modified radiation pattern [5].

Hybrid method: The three-dimensional ray-tracing predictor was based on both the image and ray-shooting methods. The single-room algorithm takes into account transmitting and receiving antenna radiation patterns and the characteristics of bounding areas with distinct electromagnetic properties, such as windows and doors. For maximum flexibility, the information about the position and movement of each human body present is supplied to the program by a text file. Using the image technique, the algorithm initially determines all possible propagation paths, before blocking those that intersect obstructing bodies. Any additional