

IMPROVING MULTIUSER DETECTION PERFORMANCE BY DATA FUSION

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ABSTRACT

A data fusion approach is proposed to improve the performance of Code Division Multiple Access (CDMA) multiuser detection. More reliable detection is obtained at the switching center by fusing the detected results from base stations. This method exploits the spatial diversity that already exists in the current system without increasing the amount of data transmission between base stations and the switching center. Theoretical analysis and numerical calculation demonstrate that significant improvement of performance can be achieved.

1. INTRODUCTION

For terrestrial wireless transmission in cellular communication services, the performance and capacity of a system is determined by the following factors: co-channel interference, multi-path fading, shadowing and distance attenuation [1]. The near-far problem of interference can be efficiently solved by sophisticated multiuser detectors [2]. Micro-diversity combination techniques [3], [4] have proved to be effective in alleviating the effect of multiple path on system performance. Macro-diversity, or base station diversity [4], [5], is a good approach to combat shadowing effect and distance attenuation. The multiuser detector achieves significant performance improvement over the conventional detector (single user detector) by performing joint detection on all users. Recently, Kandala *et al.* [6], realizing the base station diversity already existed in the current structure, proposed a multi-user and multi-sensor detector, in which each base station only calculates and transmits the sufficient statistics to a switching center. The detection is performed at the switching center, resulting in better performance. The performance gain of the diversity scheme and the multi-sensor detector is achieved by collecting and combining the information distributed among different base stations, at the expense of increased complexity and amount of information transmitted. In the existing CDMA network

structure, data are usually detected at the base station, and then only the detected bits/decisions are sent to the switch on a high-speed and highly reliable channel. It is simpler to transmit decisions to the switch, combining these decisions, rather than the sufficient statistics at the switching center, thus resulting in decreased complexity. Such an approach is known as distributed detection or data fusion, which has been applied to CDMA communication [7]. In this paper, an adaptive fusion scheme [8] is used to combine the primary decisions from individual base stations at the switching center. Each base station employs a multiuser detector to obtain the primary decisions. Section 2 describes the adaptive fusion algorithm. Two important properties of data fusion are proved in Section 3. The performance analysis for CDMA is presented in Section 4. Section 5 presents the conclusion of the paper.

2. DATA FUSION ALGORITHM

The geometrical arrangement of antennae for the new approach is the same as the typical cell geometry. A simple sectored antenna is employed at each site. Each antenna sector covers 120° azimuth. The detection is performed at each antenna sector by a multiuser detector. The detected results are sent to a switching center which, as shown in Figure 1, is shared by three simple-sectored antennae. The final detection is made at the switching center by adaptive fusion [8] based on the detected results from three separate antenna sectors covering the same area. Let $U = [u_1, u_2, u_3]$ be the vector of detected bits for a desired user. Here, $u_i \in \{1, -1\}$, (binary signaling) $i = 1, 2, 3$, is the primary decision made by the i th antenna sector. Assume synchronization has been achieved among antennae, so that u_i for $i = 1, 2, 3$, corresponds to the same information bit transmitted. The final detection at the switching center for the same information bit is denoted by u_f , which is a function of primary decisions. The determination of u_f can be viewed as a two-hypothesis detection problem with individual local decisions being

the observations. When the minimum probability of error criterion is adopted, we have

$$u_f = f(U) = \begin{cases} +1, & \text{if } \frac{P(U|H_1)}{P(U|H_0)} > \frac{q_0}{q_1}, \\ -1, & \text{otherwise,} \end{cases}$$

where H_0 and H_1 represent the following two hypotheses:

$$\begin{aligned} H_1: & \text{ the symbol } +1 \text{ is transmitted,} \\ H_0: & \text{ the symbol } -1 \text{ is transmitted,} \end{aligned}$$

and q_1 and q_0 are the *a priori* probabilities of these two events. Using the Bayes rule to express the conditional probabilities with further simplification, the above likelihood ratio can be expressed as

$$\frac{P(H_1|U)}{P(H_0|U)} > 1.$$

The corresponding log-likelihood ratio is

$$\lambda = \log \frac{P(H_1|U)}{P(H_0|U)} > 0.$$

Since three base stations are far away from each other, signals received at the three base stations pass through different channels, and it can be assumed that the local decisions are statistically independent, conditioned on the transmitted information. Thus, we have

$$\begin{aligned} P(H_1|U) &= \frac{P(H_1, U)}{P(U)} \\ &= \frac{q_1}{P(U)} \prod_{S^+} (1 - P_{M_i}) \prod_{S^-} P_{M_i}, \quad (1) \end{aligned}$$

where S^+ is the set of all i such that $u_i = +1$ and S^- is the set of all i such that $u_i = -1$. $P_{M_i} = P(u_i = -1|H_1)$ is the bit error probability of the user at receiver i when symbol $+1$ is transmitted. In a similar manner,

$$P(H_0|U) = \frac{q_0}{P(U)} \prod_{S^-} (1 - P_{F_i}) \prod_{S^+} P_{F_i},$$

where $P_{F_i} = P(u_i = +1|H_0)$ is the bit error probability of the user at receiver i when symbol -1 is transmitted. Thus,

$$\lambda = \log \frac{P(H_1|U)}{P(H_0|U)} = \log \frac{q_1}{q_0} + \sum_{S^+} \frac{1 - P_{M_i}}{P_{F_i}} + \sum_{S^-} \frac{P_{M_i}}{1 - P_{F_i}}.$$

Therefore,

$$u_f = f(U) = \begin{cases} +1, & \text{if } \lambda = a_0 + \sum_{i=1}^3 a_i u_i > 0, \\ -1, & \text{otherwise,} \end{cases} \quad (2)$$

where

$$a_0 = \log \frac{q_1}{q_0}, \quad (3)$$

$$a_i = \begin{cases} \log \frac{1 - P_{M_i}}{P_{F_i}}, & \text{if } u_i = +1, \\ \log \frac{1 - P_{F_i}}{P_{M_i}}, & \text{if } u_i = -1. \end{cases} \quad (4)$$

For the binary symmetric channel (BSC) and equiprobable source, $P_{F_i} = P_{M_i}$ and $a_0 = 0$.

Since the probabilities at each antenna is unknown and time-varying, the following adaptive algorithm is introduced to perform the fusion operation [8]:

$$\begin{aligned} a_0 &\approx \log \frac{m}{n} \\ a_i &\approx \begin{cases} \log \frac{m_{1i}}{n_{1i}} - a_0, & \text{if } u_i = +1, \\ \log \frac{m_{0i}}{n_{0i}} + a_0, & \text{if } u_i = -1, \end{cases} \quad (5) \end{aligned}$$

where m is the number of the events that $u_f = 1$, n the number of the events that $u_f = -1$,

m_{1i} the number of $u_i = +1$ and $u_f = +1$,

m_{0i} the number of $u_i = -1$ and $u_f = -1$,

n_{1i} the number of $u_i = +1$ and $u_f = -1$,

n_{0i} the number of $u_i = -1$ and $u_f = +1$.

3. PERFORMANCE ANALYSIS

From Section 2, it can be seen that the detected result at the switching center is based on the optimal combination of information from three totally different channels. Thus, better performance is expected from the data fusion method. The following analysis considers shadowing only. The reason for not including the fading effect is that each base station is usually equipped with a diversity receiver (e.g. RAKE receiver), in which case, the fading due to multipath is greatly reduced. The signal out of a diversity combiner is a good representation of the average signal level (local mean), which is dominated by shadowing. It is well known that the signal power, and thus the signal-to-noise ratio (SNR) are random variables [1] solely because of shadowing. The deviation of the signal power caused by shadowing usually ranges from seconds to hours. It is quite slow compared to the bit rate (e.g., 9600 bit/sec). Within a short period, SNR can thus be treated as a constant. Thus, the bit error probability (or BER) at the base station and switching center exhibits the following important property.

Proposition 1 Denote the bit error rate (BER) for a user at each antenna site in a BSC for equiprobable sources as R_i , $i=1,2,3$. Then the bit error rate achieved at the fusion center, R_b , for the same user is

$$R_b = \min\{R_m, R_1, R_2, R_3\}, \quad (6)$$

where $R_m = R_1R_2 + R_1R_3 + R_2R_3 - 2R_1R_2R_3$.

Proof

The user index is omitted for notational simplicity. For equiprobable sources and BSC, $a_0 = 0$ and $P_{M_i} = P_{F_i} = R_i$. Thus, from Eq. (2),

$$\lambda = \sum_{i=1}^3 (a_i) u_i = \sum_{i=1}^3 \log\left(\frac{1-R_i}{R_i}\right) u_i. \quad (7)$$

According to the optimal fusion rule, the bit error probability at the fusion center is

$$R_b = \frac{1}{2}[P(\lambda > 0|H_0) + P(\lambda < 0|H_1)], \quad (8)$$

where H_0 , H_1 represent the events that symbols -1 and $+1$ are transmitted, respectively. Without loss of generality, let $R_1 < R_2 < R_3$. Thus, $a_1 > a_2 > a_3$, implying that

$$\lambda \begin{cases} > 0 & \text{if } U^t = [1, 1, 1]^t, [1, 1, -1]^t \text{ or } [1, -1, 1]^t, \\ < 0 & \text{if } U^t = [-1, 1, -1]^t, [-1, -1, 1]^t \\ & \text{or } [-1, -1, -1]^t, \\ \text{either} & \text{if } U^t = [1, -1, -1]^t \text{ or } [-1, 1, 1]^t. \end{cases} \quad (9)$$

The above "either" case can further be deduced to the following two cases:

		U^t	
		$[1, -1, -1]^t$	$[-1, 1, 1]^t$
λ	Case (1)	> 0	< 0
	Case (2)	< 0	> 0

Case (1) implies that

$$\log\left(\frac{1-R_2}{R_2}\right) + \log\left(\frac{1-R_3}{R_3}\right) < \log\left(\frac{1-R_1}{R_1}\right), \quad (10)$$

and thus

$$R_1 < R_1R_2 + R_1R_3 + R_2R_3 - 2R_1R_2R_3 = R_m. \quad (11)$$

Hence,

$$\begin{aligned} P(\lambda > 0|H_0) &= R_1R_2R_3 + R_1R_2(1-R_3) + \\ & R_1(1-R_2)R_3 + R_1(1-R_2)(1-R_3) \\ &= R_1R_2 + R_1(1-R_2) = R_1. \end{aligned} \quad (12)$$

Likewise, by the symmetry of error probability for each channel,

$$P(\lambda < 0|H_1) = R_1.$$

Therefore,

$$R_b = \frac{1}{2}(P(\lambda > 0|H_0) + P(\lambda < 0|H_1)) = R_1 \leq R_m.$$

Similarly, case (2) implies that

$$a_2 + a_3 > a_1 \implies R_1 > R_m. \quad (13)$$

In this case,

$$\begin{aligned} P(\lambda > 0|H_0) &= R_1R_2R_3 + R_1R_2(1-R_3) + \\ & R_1(1-R_2)R_3 + (1-R_1)R_2R_3 \\ &= R_1R_2 + R_1R_3 + R_2R_3 - 2R_1R_2R_3 \\ &= R_m. \\ P(\lambda < 0|H_1) &= P(\lambda > 0|H_0) = R_m \end{aligned} \quad (14)$$

Therefore, $R_b = R_m < R_1$.

Combining these two cases, we have

$$R_b = \min\{R_1, R_m\}. \quad (15)$$

In conclusion, $R_b = \min\{R_m, R_1, R_2, R_3\}$.

Proposition 1 shows that the instantaneous BER at the switching center is less than or equal to the minimum instantaneous BER of each receiver at the three base stations. The BERs at both the base station and switching center, which are random variables because of the shadowing effect, can not be approximated as constants over a large scale. The outage probability is introduced to measure the performance of a detection scheme, and is defined as the probability of BER exceeding a certain threshold. The next proposition shows the relationship of the outage probability in the base station and the switching center.

Proposition 2 If P_1, P_2 , and P_3 are denoted as the outage probabilities of a user at antenna site 1, 2, and 3, respectively, the outage probability at the fusion center, P_b , is

$$P_b < P_1P_2P_3. \quad (16)$$

Proof

According to fundamental statistics [9] (pp. 182-184), let $r > 0$ denote the protection margin. According to the definition of outage probability and Proposition 1, we have

$$\begin{aligned} P_b &= P(R_b > r) = P(\min(R_1, R_2, R_3, R_m) > r) \\ &= P(R_1 > r, R_2 > r, R_3 > r, R_m > r) \\ &< P(R_1 > r, R_2 > r, R_3 > r, R_m > 0) \end{aligned}$$

Since

$$P(R_1 > r, R_2 > r, R_3 > r, R_m > 0) = \\ P(R_1 > r, R_2 > r, R_3 > r),$$

$$P_b < P(R_1 > r, R_2 > r, R_3 > r) = \\ P(R_1 > r)P(R_2 > r)P(R_3 > r) = P_1P_2P_3.$$

Proposition 2 shows that the outage probability at the fusion center is less than the product of the outage probability at the three antenna sectors.

4 THE PERFORMANCE IMPROVEMENT OF A CDMA NETWORK

In this paper, a multiuser detector is referred to as the one which completely eliminates the multiuser interference, such as the decorrelating detector [2]. The outage probability at each base station is

$$P_{out} = P(BER > \alpha) = P\left(\frac{E_b}{N_0} < \beta\right),$$

where E_b is the bit energy, N_0 is the variance of the additive noise at the input of the detector, and β is the protection margin when BER is α . For voice, it is adequate to set $\alpha = 10^{-3}$. When only shadowing is considered, the bit energy can be determined by

$$E_b = \frac{P_t r^{-\mu} 10^{\frac{\zeta}{10}}}{R_a},$$

where P_t is the transmitted power by the mobile user, r is the distance between a base station and the mobile, R_a is the bit rate, and μ is the distance attenuation factor. μ is usually set to 4 for urban mobile communication. ζ is modelled as a Gaussian random variable with a mean of zero and a variance of σ_s . Usually, σ_s ranges from 6 to 12 dB. Hence, the outage probability can be determined by

$$P_{out} = Q\left(\frac{1}{\sigma_s} 10 \log \frac{P_t}{\beta R_a N_0 r^\mu}\right). \quad (17)$$

According to the analysis in the previous section, the outage probability of the multiuser detector is,

$$P_{out} = Q\left(\frac{1}{\sigma_s} 10 \log \frac{P_t}{\beta R_a N_0 \min(r_1, r_2, r_3)^\mu}\right), \quad (18)$$

where r_1 , r_2 and r_3 refer to the distances between the particular mobile user and three respective base stations surrounding it. When the data fusion scheme is used, the upper bound of outage probability becomes

$$P_{out} = \prod_{i=1}^3 Q\left(\frac{1}{\sigma_s} 10 \log \frac{P_t}{\beta R_a N_0 r_i^\mu}\right). \quad (19)$$

Figure 2 plots the ratio of the required transmitted power over noise for the multiuser detector versus the spatial position of the mobile user within one cell when the outage probability P_{out} is kept as 0.1. In this figure, the bit rate is set to 9600 bit/s, $\beta=5$ (7dB), $\sigma_s = 8$ dB. The cell radius is normalized to 1. Figure 3 is the corresponding plot for the data fusion scheme. In this case, P_t/N_0 is determined by solving Eq. (19) numerically. Figure 4 shows the power gain (in dB) of the fusion method over the multiuser detector, obtained by dividing the required transmitting power for the multiuser detector over that for the fusion method under the same environment. Note that significant performance improvement is achieved by data fusion especially at the boundary region in which the multiuser detector has the worst performance. From Figure 3, it can be seen that the dynamic range of the required transmitting power is much smaller by the data fusion approach than that by the multiuser detector.

CONCLUSION

We have proposed a fusion approach making use of the diversity already existed in the current structure to improve the performance of CDMA detection. Unlike other approaches, this method can be incorporated into the current network structure without increasing the amount of information transmitted. It is demonstrated, by analysis and numerical results, that this approach minimizes the effect of distance attenuation and shadowing significantly.

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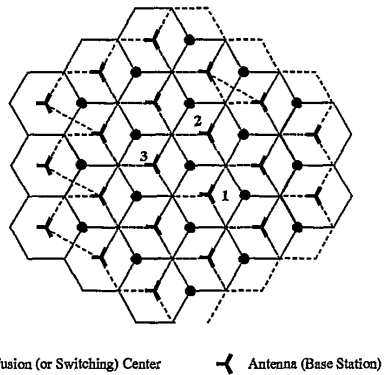


Figure 1: A data fusion CDMA detection scheme.

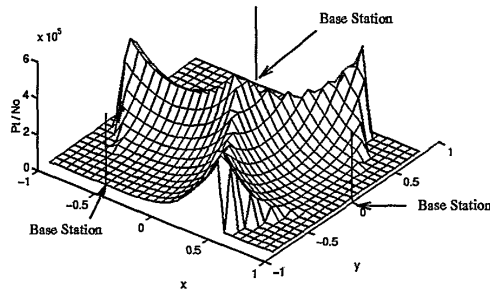


Figure 2: Required transmitting power using the multiuser detector.

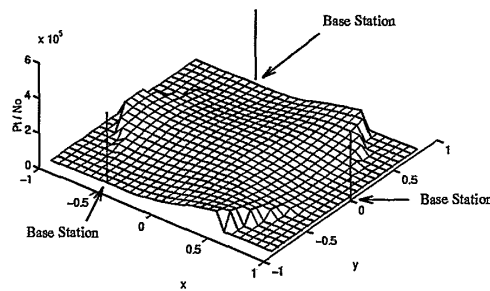


Figure 3: Required transmitting power using the data fusion approach.

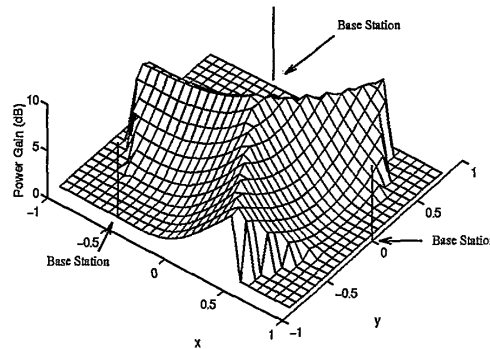


Figure 4: Power gain of the data fusion over multiuser detector.