Adaptive Selection Combining for Soft Handover in OVSF W-CDMA Systems

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***Abstract*—In W-CDMA, soft handover is supported at cell boundaries to maintain communication quality. The *maximal ratio combining (MRC)* and *generalized selection combining (GSC)* [1], [2] are two possible approaches. However, soft handover is resource-intensive. In this letter, we propose an *adaptive selection combining (ASC)* scheme that can switch flexibly between MRC and GSC so as to take care of both channel loading and communication quality. The signal-to-interference-and-noise ratio (SINR) is kept as high as that of MRC while the blocking probability can remain at about the same level as that of GSC.**

***Index Terms*—Active set, orthogonal variable spreading factor (OVSF), selection combining, soft handover, W-CDMA.**

I. Introduction

ONE important feature of W-CDMA is *soft handover*, which is supported by simultaneously delivering data to a mobile terminal from multiple base stations in the *active set*. Soft handover is resource-intensive. In [1], [2], two approaches, *maximal ratio combining (MRC)*, which always tries to use all base stations in the active set to deliver data, and *generalize diversity combining (GSC)*, which only uses the k stations with the highest signal quality to deliver data, are compared. MRC can support higher communication quality, but will impose higher channel loading. On the contrary, GSC is able to reduce channel loading (and thus call blocking), but may suffer from higher bit error rate (BER) due to less signal combining effect.

In W-CDMA, wireless resources can be represented by *orthogonal variable spreading factor (OVSF)* codes in a code tree. Efforts should be made to best utilize these codes. For example, code placement strategies are proposed in [3], [4] to reduce code blocking. In this letter, we propose an adaptive strategy that works in-between MRC and GSC. Our strategy also considers the allocation of codes to calls in the OVSF code tree, which is not addressed in MRC and GSC. As reported in [5], soft handover occupies about 20%–40% of a mobile terminal's connection time. Therefore, how to reduce the resource consumption of soft handover without affecting the signal quality is an important issue. Through analyses and simulations, we show that the proposed adaptive scheme support a signal-to-interference-and-noise ratio (SINR) comparable to MRC, and a call blocking probability comparable to GSC.

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II. Adaptive Selection Combining (ASC) Strategy

In W-CDMA, the *Radio Network Controller (RNC)* is responsible for soft handover, where the same piece of data is transmitted by multiple base stations simultaneously to a mobile terminal. The *active set* specifies the set of base stations with sufficiently good signal quality for a terminal. The proposed ASC strategy works in-between MRC and GSC. The basic idea is to run MRC under normal situations, but dynamically readjust to GSC when any base station in the active set is short of resource in its OVSF code tree (and thus may have to reject new calls).

In W-CDMA, each base station owns an OVSF code tree, which can be regarded as a full binary tree of height equal to the maximum spreading factor. The basic rate is denoted by $1R$. Whenever we go one level up, the rate doubles. Two codes are orthogonal if they do not have an ancestor–descendant relation.

ASC is executed when a base station receives a new call request but finds that its code tree does not have space to accommodate the call. Suppose that the requested rate is 2^jR. We will try to release some codes in the code tree that are currently supporting soft handover, so as to vacate a 2^jR code. Later on, when some calls leave the base station, it will try to rebuild the released branch to improve the soft handover quality. Consequently, ASC can reduce the call blocking probability while keeping the average SINR high.

There may exist multiple candidate codes in the OVSF code tree to be released. We only consider those that are currently supporting a soft handover call that are receiving from three or more base stations. Below, we propose three code searching strategies to release a code of rate 2^jR.

- **Exact Match:** Only candidate codes that have exactly the same rate, 2^jR, are considered. If there are multiple choices, choose any one.
- **Bottom-Up:** Candidates of all rates are considered. We search from those with lower rates to those of higher rates. The search stops once a code whose release can free a code of rate 2^jR is found.
- **Multi-Code:** We search each (busy) code of rate 2^jR in the code tree. For each code, if all its descendant codes are candidate codes, we call this code a *selectable* code. If there exist multiple selectable codes, the one who needs to release the least number of codes is chosen.

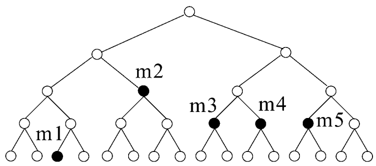

Fig. 1. Examples of code releasing strategies in ASC.

Fig. 1 shows an example, where five mobile terminals $m1, m2, m3, m4$, and $m5$ are currently supported by soft handover. If a new request for a rate $4R$ arrives, $m2$ can be selected by the Exact Match strategy, and $m1$ or $m5$ may be selected by the Bottom-Up strategy. The Multi-Code strategy may select any of these codes. However, if a new request for a rate $8R$ arrives, only the Multi-Code strategy can solve the problem (by releasing $\{m1, m2\}$ or $\{m3, m4, m5\}$).

III. Performance Analysis

In this section, we analyze the blocking probabilities of new requests for the proposed solutions. A general analysis is very difficult because the number of combinations of a code tree's states is extremely large. So we instead analyze a restricted scenario: given a code tree, it is known that there are m_i codes, $i = 0 \ldots h$, each of rate 2^iR, being occupied in the code tree. Locations of these occupied codes are considered as random variables. In the analysis, we assume that $l \geq 3$ is the number of diversity branches used in MRC, and for ASC we only need to keep the largest k diversity branches with $k < l$ when necessary.

We start with the Exact Match strategy. Let P_{mrc}^j be the blocking probability of the MRC strategy when a new call requesting rate $2^j R$ arrives. Let P_l be the probability that a code is supporting soft handover with diversity branches $l \geq 3$. Then the probability that a rate-2^jR code is releasable to support ASC is $P_r = (l - k/l) \times P_l$. Since there are m_j candidate codes, the probability that there exists no releasable code can be approximated by $E^j = (1 - P_r)^{m_j}$. So the new call blocking probability of the Exact Match strategy for rate-2^jR calls is

$$P_E^j = P_{\text{mrc}}^j \times E^j = P_{\text{mrc}}^j \times (1 - P_r)^{m_j}.$$

For the Bottom-Up strategy, the blocking probability can be expressed as $P_B^j = P_{\text{mrc}}^j \times B_{\text{low}}^j \times E^j \times B_{\text{high}}^j$, where B_{low}^j (resp., B_{high}^j) is the failure probability to vacate a 2^jR code by releasing one $2^i R$ code such that $i < j$ (resp., $i > j$). B_{high}^j can be derived by repeatedly applying the Exact Match strategy to release one $2^{j'}$R code such that $j' > j$:

$$B_{\text{high}}^j = E^{j+1} \times E^{j+2} \times \cdots E^h = (1 - P_r)^{\sum_{j'=j+1}^{h} m_{j'}}.$$

Hence, $P_B^j = P_{\text{mrc}}^j \times B_{\text{low}}^j \times (1 - P_r)^{m_j} \times (1 - P_r)^{\sum_{n=j}^{h} m_n}$. Note that B_{low}^j can be expressed in terms of $(1 - P_r)$,

$$B_{\text{low}}^j = (1 - P_r)^{N_{\text{one}}^j}$$

where N_{one}^j is the expected number of level-j unoccupied subtrees with exactly one occupied code

$$N_{\text{one}}^j = \left(2^{h-j} - \sum_{n=j}^{h} (2^{n-j} \cdot m_n)\right) \times P_{\text{one}}^j.$$

$P_{\text{one}}^j = \sum_{i=0}^{j-1} P_{\text{one}}^{j,i}$ is the probability that a level-j subtree containing exactly one occupied code, where $P_{\text{one}}^{j,i}$ is the probability that there is exactly one rate-$2^i R$ occupied code under a level-j subtree

$$\begin{aligned} P_{\text{one}}^{j,i} &= \left(\prod_{t=i+1}^{j-1} \left(1 - P_{\text{occ}}^t\right)^{2^{j-t}}\right) \\ &\quad \times \left(2^{j-i} \times P_{\text{occ}}^i \times \left(\left(1 - P_{\text{occ}}^i\right) \times \prod_{t=0}^{i-1} \left(1 - P_{\text{occ}}^t\right)^{2^{i-t}}\right)^{2^{j-i}-1}\right) \end{aligned}$$

where the first term is the probability that the subtree is not occupied from level $j - 1$ to $i + 1$ and the second term is the probability that there is exactly one level-i code in the subtree. The P_{occ}^i is defined to be a level-i code being occupied by a 2^iR call under the condition that the code is not occupied by a call of a higher rate

$$P_{\text{occ}}^i = \frac{m_i}{2^{h-i} - \sum_{n=i+1}^{h} 2^{n-i} m_n}.$$

For the Multi-Code strategy, the blocking probability can be approximated by $P_M^j = P_B^j \times M^j$, where M^j is the failure probability that no level-j subtree containing more than one occupied code is releasable under the condition that the Bottom-Up strategy fails. The number of candidate level-j subtrees that can be considered for multi-code releasing is $x_j = (2^{h-j} - \sum_{n=j}^{h} (2^{n-j} \cdot m_n)) - N_{\text{one}}^j$. The expected total number of codes that may reside in these x_j subtrees is $N_T^j = (\sum_{i=0}^{j-1} m_i) - N_{\text{one}}^j$. The expected number of codes in each subtree is N_T^j / x_j. So M^j can be approximated by $(1 - P_r^{N_T^j / x_j})^{x_j}$. The new call blocking probability of the Multi-Code strategy for rate-2^jR calls is

$$P_M^j = P_{\text{mrc}}^j \times (1 - P_r)^{(N_{\text{one}}^j + \sum_{n=j}^{h} m_n)} \times \left(1 - P_r^{N_T^j / x_j}\right)^{x_j}.$$

To verify our analysis, we simulate a code tree of a maximum spreading factor of 256 by assuming $l = 3, k = 2, P_r = 0.1$, and the maximum request rate $= 2^3 R$. We consider three combinations $(m_0, m_1, m_2, m_3) = (24, 24, 6, 6), (12, 12, 12, 12)$, and $(4, 4, 16, 16)$. Fig. 2 compares our analytical results against simulation results on blocking probabilities. Note that for the simulation part, m_i codes of rate 2^iR, $i = 0 \ldots 3$, are generated to the code tree in a random manner. As can be seen, the analytical blocking probabilities are quite close to those simulation ones. Also, in all combinations, the Multi-Code strategy outperforms the Bottom-Up strategy, which in turn outperforms the Exact strategy. For example, the blocking probabilities for

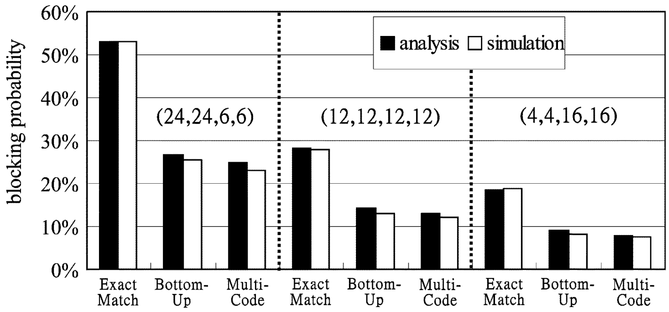

Fig. 2. Comparison of blocking probabilities obtained via analyses and simulations.

pattern $(24, 24, 6, 6)$ are $0.53P_{\mathrm{mrc}}^{j}$, $0.27P_{\mathrm{mrc}}^{j}$, and $0.25P_{\mathrm{mrc}}^{j}$, respectively, for the three strategies when $j = 3$.

IV. Simulation Results

The above analysis is not general enough in the sense that the derived blocking probability is only for a given code tree status. In general, we would like to know the long-term blocking probability and SINR when adopting our ASC strategy. A simulation environment with 72 hexagonal cells has been built. Each cell has a side length of 2 Km. The maximum spreading factor is 256. Calls arrive by a Poisson process with a certain mean rate. Call duration time follows an exponential distribution with a mean of 100 seconds. Each call may request a rate of 1R, 2R, 4R, or 8R with an equal probability of 0.25. Each call, when being generated, will move in a constant speed uniformly distributed from 0–60 Km/hr with a randomly generated roaming direction (but fixed throughout the call duration). We calculate the Ec/Io and the downlink Eb/Io using the approaches in [6], [7]. The maximum base station powers are set to 43 dBm. The maximum and minimum transmit powers per traffic channel are 30 dBm and 10 dBm, respectively. The pilot channel powers are 30 dBm. The downlink traffics are assumed to be fully orthogonal. The soft handover margin is set to 8 dB. The propagation model is $r^{-\mu}10^{\xi/10}$, where r is the distance to base station, and μ is 3.0, and ξ is the lognormal shadowing with zero mean and 8 dB standard deviation. The *transmit power control (TPC)* is conducted by increasing 1 dB if the received Eb/Io is lower than 4.5 dB and decreasing 1 dB if the Eb/Io is higher than 9.5 dB.

Fig. 3 shows the code blocking probability and power blocking probability (sum of these two probabilities is the call blocking probability). Power blocking is due to the maximum power limitation. It can be observed that MRC has the highest code blocking probability because it consumes more resources. Our Exact Match strategy does not perform well because its limited capability in searching for releasable codes. Our Bottom-Up and Multi-Code strategies perform very closely to the least resource-consuming GSC strategy in terms of code blocking probability. However, when the load is increased to 0.6 calls/s, power blocking will increase quickly for our ASC strategies and thus compensate the advantage because

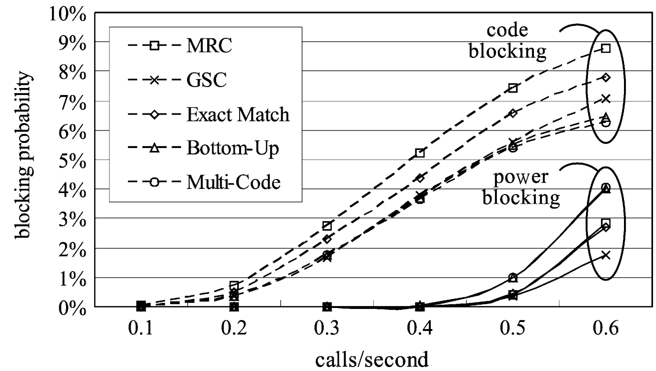

Fig. 3. Comparison of blocking probabilities.

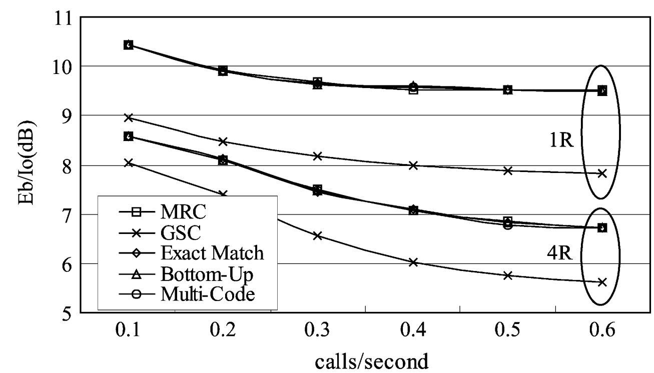

Fig. 4. Comparison of SINR.

more users are accepted by our strategies, which incurs higher interference.

Another question is whether our ASC strategies will degrade signal quality. Fig. 4 compares the SINR, expressed in terms of Eb/Io, for different strategies. While GSC performs the worst, MRC always has the best signal quality. Our three strategies perform very closely to the MRC in all simulated date rates. Owing to TPC, the SINR gaps between GSC and ASC are still kept at around 1.6 and 1.1 dB for 1R- and 4R-calls, respectively, when load is 0.4–0.6 calls/s.

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