On hard/soft handoff and macrodiversity in a CDMA mobile system

Ramon Ferrús, Pilar Díaz
Department of Signal Theory and Communications (UPC)
C/ Jordi Girona 1-3 Campus Nord-Edifici D4, 08034 Barcelona-Spain
Phone: +34-3-401 59 48 Fax: +34-3-401 72 00
e-mail: pilar, ferrus @xaloc.upc.es

Abstract **-** Soft Handoff has been shown to perform better than hard handoff in aspects like reverse link capacity and cell coverage. However, some reported comparisons include distance criteria leading to rather pessimistic performance for hard handover. This paper presents a model based exclusively on power criteria that allows a gradual and continuos transition between soft and hard handoff operation. Furthermore, in order to contrast macrodiversity benefits, some repercussions and limitations macrodiversity imposes on system design are addressed. Supporting of MRC and EGC combining techniques on the reverse link is also taken into account.

I. INTRODUCTION

Most proposals submitted to ITU for IMT-2000 standardisation are based on CDMA. Particularly, ETSI SMG2 proposal denoted as UMTS Terrestrial Radio Access (UTRA), adopts Wideband CDMA for FDD operation mode in the paired band and TD-CDMA for TDD operation mode in the unpaired band [1].

Macrodiversity operation could be stated among the most relevant features stated to defend a CDMA solution. Thus, Wideband CDMA is envisaged to support macrodiversity, and consequently soft handoff, but this possibility is left for further study in TD-CDMA where initially only a hard handoff mechanism will be mandatory. In soft handoff, the old physical channel and the new one coexist during certain period of time, whereas, in hard handoff, the old physical channel is released before the new one is established. Advantages of soft over hard handoff are mainly due to the inherent diversity gain that leads to improved power usage. But soft handoff and macrodiversity supporting has influence on system architecture envisaged for mobile access networks and normally results in higher complexity. Thus, as will be exposed in more detail in the following section, macrodiversity operation needs to be mainly justified in terms of capacity and quality improvement in front of system complexity. This paper is intended to provide a comparison concerning capacity and quality of service issues for hard and soft handover mechanisms in the reverse link. Some reported work in the literature devoted to compare both mechanisms suppose a rather pessimistic modelling for the hard handover case. Particularly in [2], a mobile in a hard handover operated system is supposed to be linked to the nearest base station without taking into account the attenuation suffered in the propagation paths to other base stations. To that end, a new modelling method is proposed for the hard handover mechanism. This model will allow us to establish a gradual transition between soft and hard handoff operation. The main criteria used to compare both handoff methods will be the outage probability, defined as the fraction of time in which quality requirements are not met.

This paper is organised as follows. Section II reports advantages and disadvantages of macrodiversity usage and some design limitations to be taken into account. Section III presents the modelling method used to analyse hard and soft handoffs. In section IV, the system model considered in this study is detailed and some results are shown in section V. Finally in section VI some conclusions are drawn.

II. CONSIDERATIONS ABOUT MACRODIVERSITY OPERATION

Macrodiversity operation needs to be evaluated under different system aspects. This section points out some considerations to be taken into account in terms of capacity, quality of service, coverage, physical layer continuity, seamless handover and different architecture issues:

A. Capacity and quality of service

In the forward link, a diversity system with Maximal Ratio Combining (MRC) could be used at the mobile receiver leading to quality improvement in the macrodiversity area. If quality is kept constant, a power reduction could be achieved. However, this power reduction does not imply directly a capacity improvement because multiple base stations are assigning resources to the same mobile station [3]. On the other hand, in the reverse link, multiple base stations could receive mobile signal and a diversity scheme could also lead to power reduction or quality improvement. But in that case, no extra resources are used and a net capacity gain could be achieved.

B. Cell coverage

If macrodiversity is used, power margin needed at cell boundary is reduced leading to higher coverage areas when the system is not capacity limited [2].

C. Physical layer service

In soft handoff, physical transmission layer could guarantee a service without interruption to higher layers. On the contrary, hard handoff could originate relatively short physical layer disruptions. However, this service interruption does not avoid the possibility of carrying out seamless handoffs for data services since link layer mechanisms could be used to mitigate it.

D. Synchronism issues

Macrodiversity operation requires synchronisation at radio frame data block level for all base stations belonging to the denoted as active set. For example, in the forward channel, the same radio data block has to be transmitted simultaneously by different base stations to allow correct combining at the mobile terminal.

E. System architecture for packet services.

The benefits of using macrodiversity for many packet services are not obvious. Best effort services or unconstrained delay data could achieve a required quality of service by means of retransmission procedures. Furthermore, services with higher bandwidth requirements in the forward channel could question macrodiversity usage. In any case, macrodiversity influences system architecture issues as location of functions related to Medium Access Control (MAC) and Radio Link Control (RLC) for packet services. Figure 1 shows a schematic architecture considered in UTRA but easily extensible to most proposals. Access networks basically could consist of controllers connected to the core network, Radio Network Controller (RNC) in UTRAN terminology, and cell sites or base stations hanging from those controllers, Node B in UTRA terminology. If macrodiversity between Nodes B is allowed, MAC and RLC functions will need to be moved to the RNC. Thus, the technology adopted needs to transport radio frames transparently up to radio link control entities placed at controllers. Furthermore, macrodiversity between base stations belonging to different controllers, and consequently having different physical transmission layer ending points, implies to dispose data streams to carry radio blocks between controllers.

F. Combining Diversity on the reverse link.

To implement a diversity scheme based on Maximal Ratio Combining (MRC) or Equal Gain Combining (EGC) methods in the reverse link, physical layer should be extended up to the macrodiversity combiner. Thus, decoding and deinterleaving functions and even demodulation should be performed out of the base stations. According to figure 2, points tagged from A to D could be possible entry points to the macrodiversity combiner. Adoption of reference point A could derive in analogue transmission of the received signal up to the combiner, or maybe, to dispose of high bandwidth digital

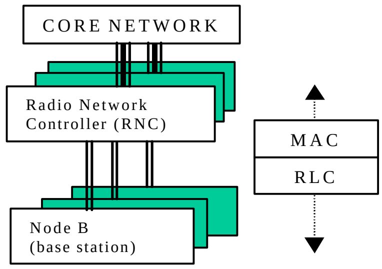

Figure 1. UTRA Access Network proposal.

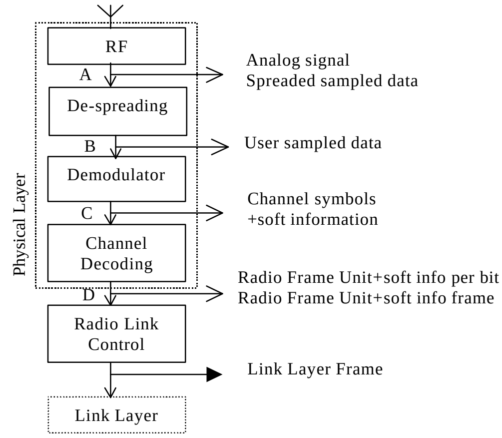

Figure 2. Basic functions performed at physical layer.

links between controllers and base stations to transfer the sampled data with enough resolution to perform MRC or EGC combining. For example, to transmit a sampled 5 MHz signal with 16 bits resolution and oversampling of 4, higher than 640 Mbits/s links will be necessary. Taking B as entry point to the combiner, sampled data after despreading could be available. A possible solution could be a kind of *distributed* RAKE between base stations and macrodiversity combiner with an important synchronism issue to be taken into account. If demodulation is performed at base stations, the combined information could consist of channel symbols with soft information. Thus, if the combiner entry point is C in figure 2, the channel decoding will be done at the combiner. With this configuration, synchronism need also to be guaranteed at symbol level and resulting performance could be better than selection diversity after decoding. In case of selection diversity, all previous mentioned functions will be done at base stations and the entry point of the macrodiversity combiner could be the one tagged D in figure 2.

III. MODELLING HANDOFF

In a hard handoff supporting system, whenever the attenuation measured from a neighbour cell is less than the active link attenuation plus a quantity denoted as hysteresis margin, a handover could be triggered. Let us denote as Hard Handover Margin (HHOM) the hysteresis margin applied. The proposed model consists of choosing randomly the current base station among which received in a determined power window. This window is fixed by the maximum received power minus the HHOM margin. A worst case is also modelled by supposing the mobile is always connected to the worst base station within the power window. This criterion is based exclusively on power values and does not consider distance conditions to evaluate the performance of the mechanism.

The soft handoff procedure could be also characterised by a power margin denoted here by Soft Handoff Margin, SHOM. This margin will be used to determine which base stations belong to the denoted as active set. Thus, the active set always contains the best base station and occasionally could include all base stations experimenting an attenuation better than the best station one minus the SHOM margin. All base stations in the active set demodulate signal transmitted by a mobile and forwards it to the macrodiversity combiner. If a selection diversity scheme is used, the best received signal will be chosen. In case of MRC or EGC combining, some of the received replicas will be mixed to obtain a better quality signal. A parameter denoted as L will be used to account the maximum number of combining branches.

Regarding hard handover margin, large HHOM could lead to mobiles connected to base stations with relatively bad fading conditions. Instead, reduced HHOM margin could increase the number of unnecessary handovers of mobiles moving around boundary zones. Theoretically, a HHOM set to zero means that the mobile terminal is always connected through the strongest base station, despite 'ping-pong' effect is maximum. For the soft handover case, a large SHOM leads to unnecessary resources devoted to a mobile by many base stations because of the practically nonexistent improvement in a diversity system when the power difference is too large. Instead, a small SHOM means that only signal with similar power levels will be combined, but the cells belonging to the active set could change rapidly. Setting also the SHOM to zero, only the best base station would assign power to the mobile terminal. The similar behaviour of both methods, when small margins are considered could be used to define a gradual transition between soft and hard handoff. This 'natural' transition is schematically represented in figure 3.

IV. SYSTEM MODEL

The received E_b/N_0 for a mobile terminal *i* in a cellular system connected through a reference base station, BS_0, could be expressed by

$$\left(\frac{E_b}{N_o}\right)_i \approx G_p \frac{P_r^i}{\sum_{j=1}^{M} P_r^j - P_r^i + h} \qquad (1)$$

where P_r^i is power received from mobile *i*, M refers to the number of simultaneous transmissions in all the coverage area, G_p is the processing gain and η represents

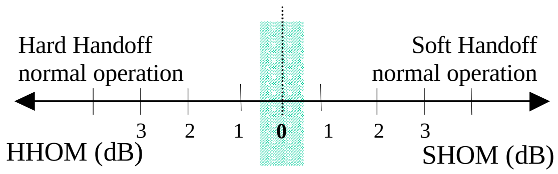

Figure 3. Gradual transition between hard and soft

the background noise. As we are intended to provide results independently of distance criteria, interference will be addressed as a whole, that is, without splitting inner-cell from outer-cell interference. To calculate the received power from each mobile, the propagation model used consists of the product of the distance to the μth power and a lognormal component accounting for shadowing losses. Rayleigh fading components are not included since they are supposed to be computed in the required bit energy-to-interference ratio. Thus, the received power at BS_0 from any mobile *j* will be

$$P_r^j = P_t^j \cdot r_{oj}^{-m} \cdot 10^{\frac{z_{oj}}{10}} \qquad (2)$$

where P_t^j is the transmitted power, r_{oj} is the distance between mobile *j* and BS_o and ζ_{oj} accounts for the shadowing in the given path. Assuming that mobile *j* is power controlled by base station *t*, the transmitted power is given by

$$P_t^j = max\left(P_{max}, S^j r_{tj}^m 10^{-z_{tj}/10}\right) \qquad (3)$$

where S^j refers to the target received power for mobile *j* and P_{max} could take into account power limitations of the mobile equipment. If no limitations in maximum power control are considered, substituting (2) and (3) in (1) we obtain

$$\left(\frac{E_b}{N_o}\right)_i \approx G_p \frac{S^i}{\sum_{\substack{j=1\\ j\neq i}}^{M} S^j \left(\frac{r_{tj}}{r_{oj}}\right)^m 10^{\frac{z_{oj}-z_{tj}}{10}} + h} \qquad (4)$$

where *t* refers to the different base stations each mobile *j* could be linked to. Following the procedure described in [4], we can rewrite expression (4) as a total interference bound to accomplish the required quality of service for mobile i yielding

$$\bar{I}_{Total} = \sum_{\substack{j=1\\ j\neq i}}^{M} \frac{S^j}{S^i} \left(\frac{r_{tj}}{r_{oj}}\right)^m 10^{\frac{z_{oj}-z_{tj}}{10}} \leq \frac{G_p}{\left(\frac{E_b}{N_o}\right)_{req}} - \frac{h}{S^i} = d \qquad (5)$$

Obtaining the mean and standard deviation from the normalised interference $\bar{I}_{Total}$, we can use the Central Limit Theorem to approximate the sum by a Gaussian random variable. The fairness of such approximation will depend on how large is M but, as we are interested in system capacity values, this condition will be normally held. Thus, the outage probability could be estimated by

$$p_{out} = Q\left(\frac{d - mean(\bar{I}_{Total})}{std(\bar{I}_{Total})}\right) \quad (6)$$

If it is assumed that mobile terminals are uniformly distributed in the coverage area and the required energy-to-interference bit ratio is the same for all mobiles, the target power fixed by the power control could be supposed equal to S for each mobile. In [4] integral expressions to be solved by numerical methods are given to calculate the total other-cell interference. The critical point to calculate the first and second moment of $\bar{I}_{Total}$ is the random nature of the subindex *t*. This index is used to denote the base station in charge of power controlling mobile *j*. The approach detailed in [4] consists of taking *t* as the nearest base station and in [2] the mechanism is extended to the nearest N_c base stations. This approach could be useful to evaluate soft handoff performance but leads to pessimistic results for hard handoff since it is modelled assuming that the mobile *j* is always connected to the nearest base station. However, trying to obtain closed expressions using power criteria to assess hard handoff performance as modelled in section III and, furthermore, dealing with combining diversity techniques instead of selection diversity, does not lend itself to analysis. For that reason, we have decided to calculate mean and variance of $\bar{I}_{Total}$ by means of Monte Carlo simulations. To untie completely system dependent parameters and number of users from random behaviour due to shadowing, the calculated parameter, denoted as y, has been $\bar{I}_{Total}$ normalised by the number of users per sector N. Thus, y depends only on shadowing and handoff mechanism used. The following approximations could be used for N close to capacity limits

$$mean(\bar{I}_{Total}) \approx N \cdot mean(y) \quad \mathrm{var}(\bar{I}_{Total}) \approx N \cdot \mathrm{var}(y) \quad (7)$$

Let us assume a cellular system with K=37 hexagonal cells distributed in tiers around a central base station, BS_0, taken as reference. $M=N \cdot K_1$ users are distributed randomly in the coverage area of the $K_1=19$ inner base stations. After calculating fading between mobiles and each base station, the current cell or active set is determined for each mobile and the transmitted power could be calculated. Interference generated by all transmissions is obtained at BS_o. The candidate cell selection and the transmission power will depend on the handoff mechanism used. Thus,

A. Hard Handover.

The current base station is selected randomly among all received within the power window fixed by the best base station and the HHOM margin. The transmitted power is calculated using (3).

B. Soft Handover with Selection Diversity

The mobile data is selected from the best base station in the active set. The transmitted power is also obtained by means of (3). Notice that the SHOM margin does not influence in performance obtained by this model since best base station is always chosen independently of the number of base stations in the active set.

C. Soft Handover with MRC combining

The number of active cells is determined by the SHOM margin. If the active set contains more than L base stations, only the L^{th} strongest are power combined. Assuming equal interference power in the L involved base stations, the transmitted power could be calculated as

$$P_t = S \cdot \left(\sum_{l=1}^{L} r_{lj}^{-m} 10^{\frac{z_{lj}}{10}}\right)^{-1} \quad (8)$$

D. Soft Handover with EGC combining

The number of active cells is calculated as for the MRC case. But now, assuming again equal interference at each branch, the transmitted power is given by

$$P_t = L \cdot S \cdot \left(\sum_{l=1}^{L} \sqrt{r_{lj}^{-m} 10^{\frac{z_{lj}}{10}}}\right)^{-2} \quad (9)$$

V. RESULTS

Statistics of y have been obtained by means of Monte Carlo simulations. Particularly, values of $K_1=19$ and N>30 have been considered. Each configuration was repeated 10000 times to be able to work with outage probabilities above 10^{-2}.

Figure 4 illustrates the behaviour of the mean of y versus HHOM and SHOM margins. We can observe the gradual transition between both methods when margins tend to zero. Notice also that the mean of the normalised interference tends to one for MRC combining with high SHOM margin. In fact, It could be shown that a MRC mechanism with unlimited combining branches tends to equal performance as achieved by an isolated cell [6].

Mean and standard deviation values for y are provided in Tables I and II for different shadowing conditions characterised by its standard deviation. Values correspond to 50 % correlated shadowing and μ=4. In Table I, the acronyms NHH and WHH refer to the normal hard handover model and the worst case hard handover model respectively as detailed in section III.

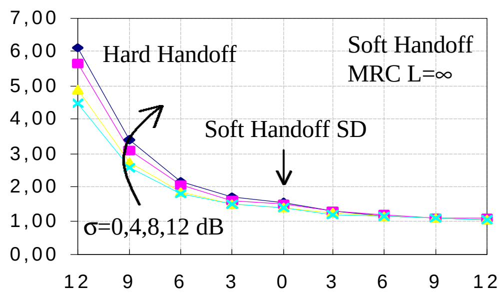

Figure 4. Mean normalised interference vs.handoff margins

Table I. Hard Handoff

HHOM(dB)		σ=4 dB	σ=8 dB	σ=12 dB
0	NHH	1,40/0,98	1,48/0,93	1,53/1,06
	WHH	1,40/0,98	1,48/0,93	1,53/1,06
3	NHH	1,41/1,04	1,59/1,02	1,67/1,16
	WHH	1,59/1,10	1,71/1,10	1,81/1,26
6	NHH	1,83/1,36	2,02/1,43	2,17/1,63
	WHH	2,31/1,68	2,60/1,86	2,87/2,12
9	NHH	2,70/2,41	3,08/2,65	3,38/2,93
	WHH	4,24/3,45	4,97/3,91	5,58/4,34
12	NHH	4,89/5,13	5,59/5,50	6,07/5,96
	WHH	9,43/7,82	10,89/8,71	12,02/9,53

Table II. Soft handoff with L=3.

SHOM(dB)		σ=4 dB	σ=8 dB	σ=12 dB
0	MRC	1,40/0,98	1,48/0,93	1,53/1,06
	EGC	1,40/0,98	1,48/0,93	1,53/1,06
3	MRC	1,21/0,93	1,26/0,82	1,28/0,94
	EGC	1,22/0,93	1,26/0,82	1,28/0,95
6	MRC	1,12/0,90	1,16/0,77	1,16/0,88
	EGC	1,14/0,91	1,18/0,78	1,18/0,89
9	MRC	1,08/0,88	1,11/0,74	1,11/0,85
	EGC	1,13/0,90	1,16/0,77	1,17/0,89
12	MEC	1,05/0,86	1,09/0,73	1,09/0,84
	EGC	1,16/0,93	1,20/0,80	1,20/0,92

The provided values could be used to evaluate the effects of handoff mechanism in capacity or quality of service. For example, let us assume N=30 users per cell and shadowing modelled by a standard deviation of 8 dB. The required δ (5) to guarantee an outage probability below 10% could be approximated using (6) by values shown in table III. In case of neglecting thermal noise and taking as a reference a SD soft handoff, hard handoff with HHOM=3-6 dB supposes a loss less than 0.4-1.5 dB in (E_b/N_o) in the normal case or 1.3-2.5 dB in the worst case. On the other hand, MRC and EGC could increase (E_b/N_o) about 1 dB for SHOM=6 dB.

Table III. Required δ for N=30 mobiles and p_{out}=10%

	HHOM (dB)		SHOM (dB)		
	6	3	0	3	6
NHH/MRC	70,7	55,6	51,0	43,8	40,6
WHH/EGC	91,2	59,1	51,0	43,8	41,0

Capacity could also be estimated fixing system parameters as G_p and minimum required (E_b/N_o). Figure 5 plots the outage probability versus the number of users for typical values of G_p=256 and (E_b/N_o)=7dB. Taking again as reference SD soft handoff supporting 30 users, hard handoff with 3-6 dB HHOM results in 3-9 less users. Instead, MRC soft handoff with 3-6 dB could support 5-8 more users.

VI. CONCLUSIONS

Macrodiversity supporting in the mobile access networks results in higher complexity and strengthens the usage of circuit oriented transmission even for packets services to deal with critical synchronisation issues. Thus,

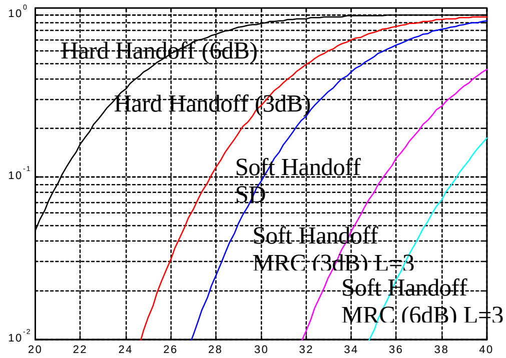

Figure 5. Outage probability versus users per cell

macrodiversity adoption needs to be mainly justified in terms of capacity and quality improvement.
A model based on power criteria, instead of distance, has been used to assess performance parameters. Provided results corroborate the better performance in capacity and quality achieved by soft handoff. However, performance differences obtained are considerably smaller than previous reported work in the literature based on distance criteria. Thus, for usual hard handoff hysteresis margin values of 3-6 dB, capacity in a soft handoff system could be about 1.1-1.4 times better. Maintaining the number of users, the improvement could be seen as a reduction of about 0.4-1.5 dB in the required signal-to-interference ratio.
MRC and EGC combining methods have been also evaluated. Capacity gains related to selection diversity of about 35% and 25% respectively could be obtained when the combiner is limited to three branches. This improvement needs to be balanced with system complexity introduced.

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