On the Satellite Diversity in CDMA based Mobile Satellite Systems

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ABSTRACT - With non-GEO constellations the primary means of counteracting the shadowing and the blockage effects is through the use of the satellite diversity, i.e. multiple satellites in the constellation are simultaneously visible to user. The probability system availability is improved by increasing the probability at least one satellite is in clear Line Of Sight. In the selection diversity (SD) scheme the user is served by one satellite selected on the basis of the better Signal to Noise Ratio. In CDMA systems the spatial diversity provided by the satellite diversity can be more effectively exploited by combining signal replica coming from satellites in view with the aim at increasing the system capacity. Actually, the performance of signal combining/selection diversity schemes depend on the specific propagation scenario and it is not always effective to combine signal replica. In this paper hybrid selection/combining diversity schemes are proposed and a performance comparison in terms of system availability and capacity enhancement is carried out. Furthermore, an analytical methodology of the Downlink of DS-CDMA systems which takes into account the power constraints of a satellite environment is described and applied for the capacity assessment of the proposed satellite diversity schemes.

1. Introduction

It is now well accepted that satellite systems will be necessary to complement terrestrial facilities to offer an *anytime anywhere* service. Most of the air-interface proposals submitted to ITU for the terrestrial IMT-2000 are based on various flavors of Wideband Code Division Multiple Access (W-CDMA) [1]-[4]. This fact constitutes an important guideline for steering the development of the satellite-component access scheme, as an air interface similarity will certainly contribute to making dual-mobile terminal more cost-effective [5]-[6]. Terrestrial systems seldom experience line-of-sight communication links; on the contrary, the capability to provide mobile satellite communications is strongly related to presence of a clear non obstructed path between satellite and user. In low-earth orbits moreover, path blockage is a very critical problem due to the low elevation angle at which satellites are seen most of the time. When there is an obstruction the systems must have a way to coping with these events. On the other hand, satellite systems are often power limited ([7],[8]) and, hence, counteracting shadowing and blockage effects by means of additional link margins may not be viable. With non-GEO constellations the primary means of coping with obstruction is through the use of satellite diversity: when communications is to be established from user to a terrestrial gateway there are usually multiple satellites in the constellation that are jointly visible to user and gateway and call can be simultaneously established through two different links-one on each satellites. If one of the links is obstructed the other link can carry the call. Therefore, satellite diversity greatly reduces the signal blockage probability as it has been confirmed during experimental campaigns whose results are summarized in [9]. If the reduction in the probability of a dropped call is the greatest benefit of the satellite diversity there is a subsidiary benefit: the satellite power per user is reduced and, hence, given the overall available on-board power, the system capacity can be increased. A meaningful quantitative assessment of the impact in terms of capacity of the satellite diversity exploitation needs the evaluation of the achievable power saving through a proper DS-CDMA downlink analysis. So far, the downlink analysis has been developed either without constraints on the limited spacecraft power [10], or under the hypothesis of full orthogonality between the spreading sequences [11]-[13]. The latter actually applies only in the case of a very low satellite load, below the codebook limit (namely, less that 256 voice users for the WCDMA radio interface). In both cases, the actual sensitivity of capacity with respect to power management strategies, as power control and satellite diversity, cannot be fully appreciated.

Furthermore, the full frequency reuse scheme, typically adopted in CDMA systems allows to exploit more effectively such a offered spatial diversity by coherently combining signal replica transmitted over multiple satellites or beams. With respect to a selection diversity scheme, a combining scheme provide an higher system availability and an increase or a decrease of the capacity on the basis of the combination of the following factors: 1) reduction of the power link margin per user; 2) increase in the number of the interference users or, from another point of view, reduction of the available satellite resources per user. In fact, when each physical user is served from two satellites the effect from the interference point of view is a doubling of the number of users. In some cases, the reduction of the power link margin and, hence, the reduction of average interference contribution per user could not compensate the increase of the actual number of interference users. Let note that the interference contribution coming from the non serving satellites in view (non synchronized interference) does not take advantage from the orthogonality of the spreading sequences. In those cases, a simple SD (Selection Diversity) scheme in which the user is served by one satellite selected on the basis of the better SNR could provide a better trade-off capacity-availability with respect to a signal combining scheme. When and when not the signal combining satellite diversity is advantageous depends on the specific propagation scenario and, hence, how often paths are obstructed and what their excess attenuation is once they are obstructed.

In this work, a novel methodology analysis of the downlink of a DS-CDMA satellite system with satellite diversity reception is described, [14]. Furthermore, two hybrid selection/combining satellite diversity schemes are proposed and compared with selection diversity and combining diversity schemes on terms of both availability and capacity in different propagation scenarios.

The paper is organized as follows. In Section 2 the methodology analysis is presented; in Section 3 the satellite diversity strategies considered are described and the quality parameters defined. Comparative results are derived and discussed in Section 4. In Section 5, the main results are summarized, conclusions and perspectives are drawn.

2. System Model and Downlink Analysis

Let us assume that a total number of users K_S are served by M satellites in visibility. For each satellite an average load of K users is uniformly distributed among N_b spot beams and N_c carriers. Each carrier is accessed according to a QPSK-based DS-CDMA. No time synchronization among the different satellite signals is assumed, so that the signals coming from different satellites generate asynchronous interference after despreading at the demodulator site. Cross polarization frequency reuse and Voice Activity Detection (VAD) are used to reduce interference. The actual orthogonality degree experienced in the downlink is assumed to be a function of the total number of users K [15]. A BER-Driven power control is considered which consists of two parts: an inner and an outer loop. The inner loop is a SIR-based power control, i.e. the receiver compares the estimated received signal to interference ratio (SIR) with a target value and commands the transmitter to increase or decrease the power accordingly. It is assumed to be able to compensate for large scale signal variations, but it is not capable to counteract the fast fading components. Hence, the received E_b/N_T after power control, where N_T includes both thermal noise and MAI (Multiple Access Interference), is still variable. Therefore, the effectiveness of the inner loop depends on the propagation conditions of the user of interest. The outer loop is needed to compensate such variability, adjusting the target SIR so that all users obtain the same performance in terms of bit error rate. Let us denote by $\mathbf{r}_{mj}(t)$ the complex envelope of the signal received by the j-th user from the m-th satellite, being satellite i the service one; neglecting the data modulation component, we have

$$\mathbf{r}_{mj}(t) = \mathbf{h}_{mj}(t)[\delta_0[m-i]\,\sqrt{2P_j}\,\mathbf{c}_j(t-\tau_{mj}) + \sum_{k=1}^{K_e^{(m)}} \sqrt{2P_k}\,\mathbf{c}_k(t-\tau_{mj})] \quad (1)$$

where $\mathbf{h}_{mj}(t) = h_{mj}(t)\exp(j\varphi_{mj})$ is the channel gain from satellite m, $\delta_0[n]$ denotes the Kronecker delta function, P_k is the power transmitted to the k-th user, $\mathbf{c}_k(t)$ denote the spreading waveforms and τ_{mj}, uniformly distributed in the signaling interval T, is the modulo-T delay from satellite m. The transmitted power P_k can be written as $P_k = P_0\,\eta_k$, where P_0 is the nominal power associated to a single user received at the satellite antenna beam center under unobstructed multipath–free conditions and η_k denotes the power advance forced by the control scheme. We assume, without loss of generality, $\tau_i = 0,\ \varphi_i = 0$. In (1), the first term is the useful one, which is not zero only if the received signal r_{mj} comes from the serving satellite, whereas the second one accounts for the MAI contribution. The residual fluctuations of the SNR after the inner loop go on jointly depending on the local shadowing attenuation (that is assumed to be compensated by the inner loop) and on the satellite load K and, hence, it depends how the power is distributed among users. In the uplink, the compensation of the shadowing attenuation can be disjoined by the control, on a statistical sense, of the fast fading component. In fact, given that the instantaneous E_b/N_T is of the form: $(E_b/N_T)_0\ g\ \chi$, where $g \triangleq h^2/\chi$ is the local mean of the channel gain, the compensation of the long term variations eliminates the dependency from this local mean. A further margin is then required to counteract the effect of the residual fast fading term χ [11]. In the downlink, the signal-to-noise ratio cannot be factored in a long term component and in a fast fading one. Hence, the computation of the average power cost per user, namely the power factors η_j, conditioned to a certain propagation scenario (local attenuation and satellite load) has to be performed by solving the following system:

$$\begin{cases} \left(\frac{E_b}{N_T}\right)^{(est)} = f_{in}^{(p_{\chi_1}\cdots p_{\chi_M})}(g_1 \ldots g_M\ ;\ \eta_j) = \Gamma \\ E\left\{Q\left(\frac{E_b}{N_T}\right)\right\} = f_{out}^{(p_{\chi_1}\cdots p_{\chi_M})}(g_1 \ldots g_M\ ;\ \Gamma) = P_e \end{cases} \quad (2)$$

In (2), $(E_b/N_T)^{(est)}$ denotes the measured signal-to-noise ratio, g_i denotes the local mean of the channel gain related to the satellite i, Γ and P_e, as previously indicated, denote the required target of E_b/N_T at the output receiver and the required error probability, respectively, $p_{\chi_m}(\chi_m)$ is the probability density function (pdf) of the fast fading component χ_m and $Q(x)$ is the complementary cumulative Gaussian distribution. The average error probability is obtained by applying the statistical operator to the non compensated fast fading components. Notice that, in (2), the first relationship models the inner loop logic, whereas the second one accounts for the outer loop effect. The measured (E_b/N_T) expressions are obtained assuming a separate observation of signal and noise, namely: $(E_b/N_T)^{(est)} = E\{E_b\}/E\{N_T\}$, where the statistical operator is intended to filter out the fast fading component. It is easy to verify that the following holds, in case of SD:

$$(E_b/N_T)^{(est)} = E_0\ \eta_j\ \frac{g_i}{N_0 + I^{(s)} g_i + I^{(us)} \displaystyle\sum_{m=1, m\neq i}^{M} g_m} \tag{3}$$

whereas, in case of MRC, we have:

$$(E_b/N_T)^{(est)} =$$

$$\frac{E_0\ \eta_j\ \left(3 \sum_{i=1}^{M} g_i^2 + 2 \sum_{i=1}^{M-1} \sum_{m=i+1}^{M} g_i g_m\right)}{N_0 \sum_{i=1}^{M} g_i + 3\, I^{(s)} \sum_{i=1}^{M} g_i^2 + I^{(us)} \sum_{i=1}^{M} \sum_{m=1, m\neq i}^{M} g_i g_m} \tag{4}$$

where $I^{(s)}$ and $I^{(us)}$ denote the interference contribution coming from serving ($m = i$) and non serving ($m \neq i$) satellites, respectively, that can be written:

$$I^{(s/us)} = E_0\ \eta\ R_u\ K\ \rho\ \alpha\ \frac{\gamma_m}{N_b\ N_c\ W} \tag{5}$$

being $E_0 = P_0/R_u$ the nominal bit energy, R_u the user data rate, W the spreading bandwidth and $\eta = E\{\eta_k\}$ the average value of the power advantage required by the power control system. Let note that, in a full load condition, each MAI term can be written as a function of the total power $P \cong K\ E_0\ \eta\ R_u\ \alpha$ received from the satellite, namely:

$$I^{(s/us)} \cong \frac{P}{W}\ \frac{\gamma_m\ \rho}{N_b\ N_c}. \tag{6}$$

According to (2), the computation of each margin η_j turns out to be conditioned to specific hypothesis about the channel state $\Theta = \Theta(g_1 \ldots g_M\ ;\ p_{\chi_1} \ldots p_{\chi_M})$, being $\Theta = \Theta^{(s)}$ with probability $p^{(s)}$, and $s = 1 \ldots S$. Assuming the probabilities $p^{(s)}$ time invariant (large population hypothesis) η_j can be modeled as a rv with probability mass function $p^{(s)}$ when $\eta_j = \eta^{(s)}$, being $\sum_{s=1}^{S} p^{(s)} = 1$. As for the satellite channel, the two state propagation model is assumed [16] for each propagation environment: where the influence of the direct component cannot be neglected, the envelope of the received signal is modeled as a Rice process; otherwise (user shadowed from the satellite) the envelope is modeled as a Rayleigh-lognormal process. The propagation environment, on its turn, is classified into L classes, basically depending on the urbanization degree and on the elevation angle ψ experienced by the user. Hence, $g_m = 1 + 1/c_l$ if satellite m is in LOS condition, being c_l the Rice factor modeling the l-th propagation environment; otherwise, g_m itself turns out to be a lognormal rv. As a matter of fact, this would lead to unlimited cardinality of the channel states set $\left\{\Theta^{(m)}\right\}$, so that the actual value of g has been replaced by its average one $g^{(av)}$, in order to access the model in its numerical form. The effect of this approximation has been found to be negligible in the overall dynamic range of the outer loop process. Hence, the long term attenuation g_i can assume the following value:

$$g_i = \begin{cases} 10^{\frac{\mu_l}{10} + \left(\frac{\sigma_l}{10}\right)^2 \frac{ln(e)}{2}} & \text{if satellite } i \text{ is shadowed} \\ 1 + \frac{1}{c_l} & \text{otherwise} \end{cases} \tag{7}$$

where μ_l and σ_l^2 denote mean and variance of the normal process which models the logarithmic expression of the long term fluctuation in the l-th environment. The residual fluctuations χ_i, on its turn, is central or non-central chi-square distributed provided that the satellite i is shadowed or not, respectively.

3. Satellite Diversity Schemes

Let introduce a threshold which bounds maximum value of the power factor η_j is assumed and denoted with η_{thr}: a user cannot be served by a satellite, if a power advance higher than η_{thr} is required. This threshold could represent the physical bound on the transmitted power but it could be also a power threshold introduced in the power control system with the aim to increase the system capacity at expense of a reduction of the availability. Let denote with D the fraction of users in the service area which can be served by at least one satellite. Let denote with K_{max} the maximum number of users which can be simultaneously served with a specified available spacecraft power. A threshold increment allows for refusing users which require high transmitter power levels to satellite and, hence, leads to a reduction of D. On the other side, further users characterized by less stringent power requirements can be served by the saved spacecraft power and, hence, an augmentation of K_{max} is provided.

A first simple scheme considered is the selection diversity scheme. At each time the user is served by one satellite selected on the basis of the better SNR. The spatial diversity provided by the satellite diversity can be more effectively exploited by combining signal replica coming from satellites in view. The availability is increased with respect to the selection diversity scheme, the link margin per user is reduced but the number of interference users is higher than one of the previous diversity scheme. A third satellite diversity scheme is considered, denoted as *hybrid1*, where the signal replica are combined only in the case of all satellites are not in LOS conditions. In that scheme, when a user is in LOS conditions with respect both satellites, interference coming from the non serving satellite is not shadowed and it does not take advantage of the combining of the signals. It could be more efficient to combine in the latter case as well. In the latter scheme introduced, *hybrid2* signal replica of all satellites in LOS conditions are combined and they are also combined when all satellites are not in LOS conditions. Each scheme is characterized by a different trade-off availability-capacity depending on the propagation scenario (i.e., urban/open areas, elevation angles).

4. Numerical results

Hereinafter, the downlink methodology analysis described in section 2 is applied to compare the introduced satellite diversity schemes in different propagation scenarios. Numerical results are derived for the voice service, according to the basic parameters of the W–CDMA radio interface [15] [17]: $W = 5MHz$, $R_u = 8kbps$, $\alpha = 0.5$, $N = 128$, $P_e = 10^{-3}$, $\rho = 0.55$ (corresponding to a cross–polarization attenuation A_ρ of 10 dB) and $\gamma_0 = 2$. As for the system parameters, a 10 beams coverage, and a single carrier system has been assumed, namely: $N_c = 1$ and $N_b = 10$, whereas the the β parameter, defined as $\beta \triangleq P/(N_0 W)$, accounts for the spacecraft power. According to approximation (6), this parameter provides an estimate of the expected interference to noise spectral density ratio, as well, directly from the basic system parameters as beam shaping and available bandwidth, namely:

$$\frac{I^{(s/us)}}{N_0} \cong \beta \, \frac{\gamma_m \, \rho}{N_b \, N_c}. \qquad (8)$$

A β value of 20 dB in the 2 GHz band, for instance, can be deemed typical of a Medium Earth Orbit (MEO) system, or a Low Earth Orbit (LEO) system with a moderate power payload (EIRP less than $30dB_W$) [7].
For sake of simplicity, a number of satellites in view $m = 2$ is considered. The described analysis requires a proper characterization of the satellite system in terms of user classes: each user can be located in urban areas with probability B_u or in open areas with probability $B_o = 1 - B_u$, so that 2 possible propagation scenarios can be envisaged, for each elevation ψ. Urban and open areas are experienced as the worst and the best case, respectively. Let us denote by $A_{u/o}$ the shadowing probability in urban/open environment. If we denote by $S^{(\psi)}$ the number of states, conditioned to a certain elevation angle ψ, a total number $S^{(\psi)} = 4$ can be envisaged in case of single satellite reception, according to the urban/open and shadowing/unshadowing hypothesis. In the case of dual-satellite diversity, for each elevation angle ψ, $S = 6$ user classes are determined, provided that both satellites are viewed by the same elevation angle. This hypothesis has been introduced just to reduce some degree of freedom in this numerical calculation, which is basically oriented towards sensitivity analysis; nonetheless, it can be easily removed. Two different elevation angle are considered, namely $\psi = 34^o$ and $\psi = 18^o$. Furthermore, the same elevation angle is assumed for both satellites in view and the channel parameters, according to the values reported in [16], are shown in the Table I and Table II.

By solving the equation system (2) and taking into account the value of η_{thr}, for each class of users s the power margin η_s is computed and the values of D and K_{max} are carried out. The performance in terms of availability and capacity of the described satellite diversity schemes are shown in Table III in the case of $\psi = 34^o$ and $\eta_{thr} = 22dB$ with a balanced distribution of users between urban and open areas, namely $B_u = B_o = 0.5$. In Table IV results for a lower elevation angle ($\psi = 18^o$) are shown and in Table V a scenario characterized by more urban users is considered. First of all, numerical results show that in the considered scenarios the signal combining in all satellite-user link conditions (i.e., MRC scheme) is not advantageous in terms of capacity. MRC and *hybrid2* diversity schemes show better performance in terms of availabil-

Table I: Channel parameters.

Environment	Channel Parameters	$\psi = 34^o$
Urban	A_u	0.58
	lognorm. mean μ (dB)	-10.6
	lognorm. s.d. σ (dB)	2.6
	Rice factor c (dB)	6.0
Open	A_o	0.008
	lognorm. mean μ (dB)	-8.8
	lognorm. s.d. σ (dB)	3.8
	Rice factor c (dB)	11.7

Table II: Channel parameters.

Environment	Channel Parameters	$\psi = 18^o$
Urban	A_u	0.89
	lognorm. mean μ (dB)	-11.5
	lognorm. s.d. σ (dB)	2.0
	Rice factor c (dB)	3.9
Open	A_o	0.24
	lognorm. mean μ (dB)	-8.9
	lognorm. s.d. σ (dB)	5.1
	Rice factor c (dB)	10.2

Table III. Quality parameters with $\psi = 34^o \eta_{thr} = 22dB$ $B_u = B_o = 0.5$

	SD	MRC	hybrid1	hybrid2
D	0.34	1	0.5	1
K_{tot}	$2 \cdot 38700$	14300	52200	18300

Table IV. Quality parameters with $\psi = 18^o, \eta_{thr} = 23dB$ $B_u = B_o = 0.5$

	SD	MRC	hybrid1	hybrid2
D	0.5	1	1	1
K_{tot}	$2 \cdot 17300$	14700	16200	17800

Table V. Quality parameters with $\psi = 34^o, \eta_{thr} = 22dB$ $B_u = 0.8$

	SD	MRC	hybrid1	hybrid2
D	0.68	1	0.79	1
K_{tot}	$2 \cdot 24500$	16600	33300	20500

ity. In those schemes, the average transmitted power per user is lower due to the signal combining. The highest values of system capacity are achieved by SD schemes especially in more interference-limited systems, [7]-[8], like an urban environment (Table V) or higher elevation angles (Table III) but at expense of a noticeable reduction of the system availability. Furthermore, in such systems the better trade-off availability-capacity is achieved by the *hybrid1* diversity scheme. On the contrary, when low elevation angles are considered (in such cases typically the performance of the system are more sensitive to the power constraints than to the interference level) the better performance are achieved by *hybrid2*.

On the whole, if the main objective of the satellite diversity is the increment of the system availability, among the schemes that provide the higher system availability, the *hybrid2* scheme provides also better performance in term of capacity in all the different considered scenarios.

5. Conclusions and Perspectives

Two hybrid satellite diversity scheme are described. Through a downlink analysis which takes properly into account the power management strategies applied, a comparison of the proposed schemes with the classical SD and MRC schemes is performed, both in terms of reduction of the probability of a call dropped and system capacity. The quality parameters D (availability) and K_{max} can become conflicting. Numerical results show that, the MRC schemes provide higher system availability, but they are not advantageous in terms of capacity. On the other hand, SD schemes provide better performance in terms on capacity. In the proposed hybrid selection/combining diversity schemes the system availability increase is achieved through a less reduction of the capacity with respect the SD diversity scheme. Anyway, the trade-off availability-capacity for each scheme depends on the propagation scenario. In interference-limited system (urban areas) SD schemes and *hybrid1* diversity schemes provide a better trade-off performance with respect to the *hybrid2* diversity scheme (signal replica of all satellites in LOS conditions are combined; the signal replica are also combined when all satellites are not in LOS conditions). On the other hand, the latter scheme is more effective when low elevation angle are considered. Furthermore, among the schemes that provide the higher system availability, the *hybrid2* scheme provides also better performance in term of capacity in all the different considered scenarios.

The above-mentioned considerations have encouraged us to investigate a power control strategy that allows for exploiting more effectively the satellite diversity in different propagation scenarios. This is an on-going activity of the Authors' as the extension of such a comparative analysis to more realistic scenarios (higher order diversity, different elevation angles for satellites in view)

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