On the Optimum Traffic Allocation in Heterogeneous CDMA/TDMA Networks

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***Abstract*— This paper presents the optimum user allocation in heterogeneous scenarios with CDMA and TDMA technologies in order to minimize the total outage probability in the uplink. An analytical model reflecting the different nature of the two access technologies is presented in order to formulate the optimization procedure. It is shown how the optimum allocation depends on the specific parameters of the two technologies, as illustrated with some representative results. The proposed optimization methodology is claimed to have applicability in the field of Common Radio Resource Management strategies for Beyond 3G networks.**

***Index Terms*— Common radio resource management (CRRM), heterogeneous networks, beyond 3G networks, code division multiaccess, time division multiaccess.**

I. Introduction

THE coexistence of several radio access technologies (RATs) in the current and future wireless scenarios introduces an additional dimension to achieve an efficient exploitation of the scarce available radio resources. RATs differ from each other by air interface technology, services, price, access, coverage and ownership. The complementary characteristics offered by the different radio access technologies make possible to exploit the diversity gain leading to a higher overall performance than the aggregated performances of the standalone networks. Clearly, this potential gain of Beyond 3G (B3G) systems can only turn into reality by means of a proper management of the available radio resources. Common Radio Resource Management (CRRM) refers to the set of functions that are devoted to ensure an efficient and coordinated use of the available radio resources in heterogeneous networks scenarios [1][2]. More specifically, CRRM strategies should ensure that the operator goals in terms of coverage and Quality of Service (QoS) are met while providing as high as possible overall capacity. Within CRRM, the traffic allocation in the proper RAT, either at session initiation or by switching ongoing connections from one RAT to another by means of the so-called vertical or inter-RAT handover procedure, is one of the key enablers to properly manage the heterogeneous radio access network scenario. Depending on the time scale of operation of CRRM this RAT selection procedure can be done on a long-term basis or even operating on short time-scales in joint or common scheduling algorithms. As an example, in the case that the considered access technologies are UMTS (Universal Mobile Telecommunications System) and GSM/GPRS (Global System for Mobile communications/General Packet Radio Service) the inter-RAT handover procedure is specified in [3] and basically consists on a message exchange between the corresponding radio controller entities of the two networks in order to allocate resources in one or the other technology. Nevertheless, the specific algorithms to decide the execution of this procedure are implementation-dependent.

Manuscript received March 8, 2006; revised June 22, 2006; accepted June 31, 2006. The associate editor coordinating the review of this paper and approving it for publication was R. Mallik. This work has been performed in the framework of the project IST-AROMA (http://www.aroma-ist.upc.edu), which is partly funded by the European Community. The work is also partially funded by the Spanish Research Council (CICYT) under COSMOS grant (ref. TEC2004-00518, Spanish Ministry of Science and Education and European Regional Development Fund).

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Digital Object Identifier 10.1109/TWC.2007.06030032.

Different works of the research community have covered in the open literature the RAT selection in heterogeneous wireless networks in the recent years. In particular, user distributions based on balancing the load among RATs are discussed in [4][5]. In turn, in [6] the authors compare the load balancing principles with respect to service-based CRRM policies. Similarly, Lincke discusses the problem from a more general perspective in e.g. [7] and references therein, comparing several substitution policies and evaluating them by means of simulations. In all cases, CRRM has been targeted from a heuristic perspective.

This paper intends to establish a firm reference from an analytical perspective by providing insight into the optimal allocation of users in heterogeneous RANs (Radio Access Networks). In particular, a scenario with two complementary technologies, Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA), is considered. The optimal traffic distribution between the two technologies will be discussed depending on the specific radio transmission parameters of each. The analysis provided here can be used as the basis for the development of new RAT selection algorithms that exploit the cooperation between the two RATs leading to improved performance. Similarly, new joint scheduling algorithms where traffic is transmitted through the most convenient RAT on a short term basis could be inspired from this analysis. The study will be presented here for the uplink direction in a single isolated cell. The extension to the downlink direction and multi-cell and multi-service scenarios is left for future work, although it is thought that the concepts presented here establish a consistent basis for its extension to take these effects into account. The paper assumes that there exist equivalent radio bearers in the two technologies for providing the considered service with similar QoS (e.g. bit rate).

The rest of the paper is organized as follows. Section II presents the problem formulation and Section III the optimization procedure. Some representative numerical results are presented in Section IV and finally conclusions are summarized in Section V.

II. Problem Formulation

Assume a scenario with a circular cell with radius R (km). Two base stations corresponding to the CDMA and TDMA access technologies are co-sited in the center. The two systems operate in two different frequency bands so that no mutual interference among them exists. The total propagation loss L (dB) at distance r (km) from the base station in a typical cellular environment is given by [8][9]:

$$L = L_0 + 10\alpha \log r + S \tag{1}$$

where L_0 (dB) is a constant denoting the propagation losses at 1 Km, α is the path loss exponent ranging from 2 in the case of free space propagation up to higher values typically between 3 and 4 depending on the specific environment (e.g. antenna heights, obstacles, etc.) and S(dB) is a Gaussian random variable with mean 0 dB and standard deviation σ (dB) accounting for the shadowing. Notice that in general the parameters L_0, α and σ could be different for each technology to account for e.g. differences in the carrier frequencies of the two systems. Then, the propagation loss L(dB) of each technology is a random variable depending on the shadowing and the distribution of the distance r (i.e. the user spatial distribution).

In order to compute the Cumulative Distribution Function (CDF) and the probability density function (pdf) of the propagation loss, assume that the users are uniformly distributed in a circular cell with radius R. Then, the pdf of the distance r to the base station located at the centre of the cell is given by:

$$f_r(r) = \frac{2r}{R^2} \qquad 0 < r < R \tag{2}$$

Let define Y (dB) the path loss without including shadowing, given by:

$$Y = L_0 + 10\alpha \log r \tag{3}$$

The pdf of Y is given by:

$$f_Y(y) = \frac{\Lambda\beta}{R^2} e^{\beta y} \qquad -\infty < y < \xi \tag{4}$$

where $\Lambda = 10^{-L_0/5\alpha}$, $\beta = \ln 10/5\alpha$ and $\xi = L_0 + 10\alpha \log R$.

The pdf of the total propagation loss L(dB)=Y(dB)+S(dB) including shadowing will be then given by the convolution of (4) with a normal distribution function of mean 0 and variance σ^2, yielding:

$$f_L(x) = \frac{\Lambda\beta}{2R^2} e^{\beta x} e^{\frac{\beta^2\sigma^2}{2}} erfc\left(\frac{x-\xi+\beta\sigma^2}{\sqrt{2}\sigma}\right) \tag{5}$$

where the complementary error function $erfc(z)$ is defined as:

$$erfc(z) = \frac{2}{\sqrt{\pi}} \int_z^{\infty} e^{-t^2} dt \qquad -\infty < z < \infty \tag{6}$$

And the CDF is obtained from the integration of (5) as:

$$\begin{aligned} F_L(x) &= \frac{\Lambda}{2R^2}\left(e^{\frac{\sigma^2\beta^2}{2}} e^{\beta x} erfc\left(\frac{x-\xi+\sigma^2\beta}{\sqrt{2}\sigma}\right)\right. \\ &+ \left. e^{\beta\xi} erfc\left(\frac{\xi - x}{\sqrt{2}\sigma}\right)\right) \end{aligned} \tag{7}$$

In order to account for the fact that the parameters L_0, α, σ in (5) and (7) can be different for the TDMA and the CDMA technologies, in the following $F_{LT}(x)$, $f_{LT}(x)$ will denote the CDF and pdf, respectively, of the propagation loss in TDMA and $F_{LC}(x)$, $f_{LC}(x)$ the CDF and pdf of the propagation loss in CDMA.

On the other hand, let focus on the uplink direction and assume that, for the considered service, the capacity (i.e. the maximum number of simultaneous users) of the TDMA base station is C_T. This capacity is a hard limit posed by the amount of slots and carriers available in the cell. The bit rate of a user allocated in one slot of a given carrier is R_b. In turn, for the CDMA cell, the capacity is soft limited and therefore it depends on the maximum allowed interference. Particularly, assuming a single service and perfect power control, an upper bound for the maximum number of simultaneous users can be defined from the CDMA pole capacity according to [2]:

$$C_C = \lfloor C^* \rfloor = \left\lfloor 1 + \frac{W}{\left(\frac{E_b}{N_0}\right) R_b} \right\rfloor \tag{8}$$

where $\lfloor x \rfloor$ denotes the highest integer less than or equal to x and C^* is the pole CDMA capacity. In turn, W is the transmission bandwidth after spreading, R_b the service bit rate and E_b/N_o the target quality requirement. It is worth mentioning that this capacity limit could in practice be reduced to values below the pole capacity in order to account for e.g. intercell interference or imperfections in the power control. In such a case, the considerations presented in this paper would hold by changing the value of C_C accordingly.

In this scenario, from the point of view of a Common Radio Resource Management strategy, the total amount of resources available is $C_T + C_C$. Assume that there are a total of $U \le C_T + C_C$ simultaneous users in the scenario. According to a given RAT selection criterion, the U users will be distributed between the two technologies, so that $n_C \le C_C$ users will be allocated to the CDMA-based RAN and the remaining users, that is $n_T = U - n_C \le C_T$, will be allocated in the TDMA-based RAN. Notice that in case that there are more users than the TDMA capacity, i.e. $U > C_T$, the remaining $U - C_T$ users should be necessarily allocated in CDMA, while if there are more users than the CDMA capacity, i.e. $U > C_C$, the remaining $U - C_C$ users should be allocated in TDMA. Consequently, the range of values of n_C is from $n_{Cmin} = \max(0, U - C_T)$ to $n_{Cmax} = \min(U, C_C)$.

The problem considered here is to find the optimum pair (n_C^{opt}, n_T^{opt}) indicating the users that should be allocated in the CDMA and the TDMA cells so that the total outage probability in the scenario is minimized. The outage probability is defined as the probability that the measured signal to noise and interference ratio is below the minimum requirements and will be kept here as the QoS parameter to optimize. Other parameters like e.g. error rate, delay, etc., have a strong dependency on the outage probability in the sense that a user in outage will experience a high packet error rate and also will require more packet retransmissions for non real time services thus increasing the delay.

The outage condition in TDMA only depends on the maximum transmit power available at the mobile $P_{max,T}$ (dBm) and the sensitivity of the receiver $P_{S,T}$ (dBm), which in turn would be related to a certain background noise and signal to noise and interference requirement. Then, a TDMA user will be in outage whenever its path loss is above the following limit:

$$L_{max,T} = P_{max,T} - P_{S,T} \tag{9}$$

Hence the TDMA outage probability, θ_T, will be computed from the CDF of the path loss as:

$$\theta_T = 1 - F_{LT}\left(L_{max,T}\right) \tag{10}$$

On the other hand, assuming n_C simultaneous transmissions in CDMA, the outage condition depends on the maximum transmit power constraints, the background noise, the load factor and the path loss distribution. Particularly, as shown in [2], a user will be in outage provided that its path loss is above the limit:

$$\begin{aligned} L_{max,C}(n_C) &= P_{max,C} - P_{N,C} \\ &+ 10\log\left(1 + \frac{W}{\left(\frac{E_b}{N_0}\right)R_b} - n_C\right) \end{aligned} \tag{11}$$

where $P_{N,C}$ (dBm) is the background noise power at the receiver, and $P_{max,C}$ (dBm) the maximum available transmit power level. Consequently, the outage probability for CDMA is:

$$\theta_C(n_C) = 1 - F_{LC}\left(L_{max,C}(n_C)\right) \tag{12}$$

Then, the total outage probability θ in the scenario will be given by:

$$\theta(n_C) = \theta_C(n_C)\frac{n_C}{U} + \theta_T\frac{U - n_C}{U} = \frac{\phi(n_C)}{U} + \theta_T \tag{13}$$

where the function $\phi(n_C)$ is defined as:

$$\phi(n_C) = \left(\theta_C(n_C) - \theta_T\right)n_C \tag{14}$$

III. Traffic Allocation Optimisation

The problem of finding the optimum pair (n_C^{opt}, n_T^{opt}) can be reduced to finding the optimum number of users in CDMA n_C^{opt} since it directly yields the optimum number of users in TDMA as $n_T^{opt} = U - n_C^{opt}$. Then, from (13), the optimum n_C^{opt} is given by:

$$\begin{aligned} n_C^{opt} &= \arg\min_{n_C} \left(\theta(n_C)\right) = \arg\min_{n_C} \left(\phi(n_C)\right) \\ &= \arg\min_{n_C} \left(B(n_C)n_C\right) \end{aligned} \tag{15}$$

where n_C is defined in the range $[n_{Cmin}, n_{Cmax}]$ and $B(n_C)$ is defined as:

$$B(n_C) = \theta_C(n_C) - \theta_T = F_{LT}\left(L_{max,T}\right) - F_{LC}\left(L_{max,C}(n_C)\right) \tag{16}$$

The minimum of $\phi(n_C)$ will be either in one of the limits of the range $[n_{Cmin}, n_{Cmax}]$ or in the critical points where the derivative is 0. The derivative of $\phi(n_C)$ is given by:

$$\begin{aligned} \phi'(n_C) &= B(n_C) + \frac{10 n_C F'_{LC}\left(L_{max,C}(n_C)\right)}{(C^* - n_C)\ln 10} \\ &= B(n_C) + \frac{10 n_C f_{LC}\left(L_{max,C}(n_C)\right)}{(C^* - n_C)\ln 10} \\ &= B(n_C) - A(n_C) \end{aligned} \tag{17}$$

with:

$$A(n_C) = \frac{-10 n_C f_{LC}\left(L_{max,C}(n_C)\right)}{(C^* - n_C)\ln 10} \tag{18}$$

The critical points n^* will be those fulfilling that the derivative is equal to zero, so that

$$B(n^*) = A(n^*) \tag{19}$$

In the following, it will be shown how the functions $B(n_C)$ and $A(n_C)$ allow defining the existence and value of the optimum n_C^{opt}.

Proposition 1: The function $A(n_C)$ fulfils the condition $A(n_C) \le 0$ in all the range $[n_{Cmin}, n_{Cmax}]$.

Proof: From (18), the proof is straightforward given that the probability density function $f_{LC}(x)$ is a strictly positive function and that the range of variation of n_C fulfils the condition $0 \le n_{Cmin} \le n_C \le n_{Cmax} \le C_C \le C^*$. ■

Proposition 2: $B(n_C)$ is a monotonically increasing function of n_C.

Proof: Given that $L_{max,C}(n_C)$ is a monotonically decreasing function of n_C and $F_{LC}(x)$ is a CDF, which, by definition, is a monotonically increasing function, then $F_{LC}\left(L_{max,C}(n_C)\right)$ is a monotonically decreasing function. Therefore $B(n_C)$ as defined in (16) is a monotonically increasing function, which proves the proposition. ■

Theorem 1: If $B(n_{Cmin}) \ge 0$ the minimum of the function $\phi(n_C)$ in the range $[n_{Cmin}, n_{Cmax}]$ occurs at $n_C^{opt} = n_{Cmin}$.

Proof: From Proposition 2, if $B(n_{Cmin}) \ge 0$, this means that $B(n_C) \ge 0$ in the whole range. Furthermore, since $n_C \ge 0$, it follows that $\phi(n_C) = B(n_C)n_C$ is a monotonically increasing function and therefore the minimum occurs at n_{Cmin}. This proves the theorem. ■

Proposition 3: The derivative $\phi'(n_C)$ is a monotonically increasing function of n_C in the range $[0, C^*]$.

Proof: The proposition can be proved by showing that the second derivative $\phi''(n_C)$ is strictly positive. From (17) $\phi''(n_C)$ is given by:

$$\begin{aligned} \phi''(n_C) &= \frac{10 f_{LC}\left(L_{max,C}(n_C)\right)}{(C^* - n_C)\ln 10} \\ &+ \frac{10 f_{LC}\left(L_{max,C}(n_C)\right) C^* \ln 10}{\left((C^* - n_C)\ln 10\right)^2} \\ &- \frac{100 n_C f'_{LC}\left(L_{max,C}(n_C)\right)}{\left((C^* - n_C)\ln 10\right)^2} \end{aligned} \tag{20}$$

where the derivative of the pdf of the path loss $f'_{LC}(x)$ can be obtained from (5) as:

$$\begin{aligned} f'_{LC}(x) &= \frac{\Lambda\beta}{2R^2} e^{\frac{\sigma^2\beta^2}{2}} \left(\beta e^{\beta x} erfc\left(\frac{x - \xi + \sigma^2\beta}{\sqrt{2}\sigma}\right)\right. \\ &- \left.\frac{2}{\sqrt{2\pi}\sigma} e^{\beta x} e^{-(x - \xi + \sigma^2\beta)^2/2\sigma^2}\right) \\ &= \beta f_{LC}(x) - G(x) \end{aligned} \tag{21}$$

with $G(x)$ a strictly positive function defined as:

$$G(x) = \frac{\Lambda\beta}{\sqrt{2\pi}\sigma R^2} e^{\beta\xi} e^{-(x-\xi)^2/2\sigma^2} \tag{22}$$

Notice that the parameters β, σ, Λ and ξ in (21)(22) are those of the propagation loss for CDMA.

TABLE I

SUMMARY OF THE DIFFERENT CONDITIONS FOR THE OPTIMUM ALLOCATION

Condition			n_C^{opt}
$B(n_{Cmin}) \geq 0$			n_{Cmin}
$B(n_{Cmin}) < 0$	$B(n_{Cmin}) \geq A(n_{Cmin})$		n_{Cmin}
	$B(n_{Cmin}) < A(n_{Cmin})$	$B(n_{Cmax}) > A(n_{Cmax})$	$n_{Cmin} < n_C^{opt} < n_{Cmax}$
		$B(n_{Cmax}) \leq A(n_{Cmax})$	n_{Cmax}

TABLE II

RESULTS FOR THE CONSIDERED CASE STUDIES

	Optimum allocation		**Allocate maximum in TDMA**		**Allocate maximum in CDMA**	
	(n_C^{opt}, n_T^{opt})	**Outage probability**	(n_C, n_T)	**Outage probability**	(n_C, n_T)	**Outage probability**
Case 1	$(17, 23)$	3.59%	$(17, 23)$	3.59%	$(36, 23)$	42.40%
Case 2	$(23, 17)$	2.17%	$(17, 23)$	2.21%	$(40, 0)$	2.59%
Case 3	$(20, 0)$	1.75%	$(0, 20)$	2.61%	$(20, 0)$	1.75%
Case 4	$(14, 6)$	3.62%	$(0, 20)$	9.29%	$(16, 4)$	16.11%

The first term in (20) is a positive function because $f_{LC}(x) > 0$ and $n_C \leq C^*$. In turn, with respect to the second and third terms, their denominator is positive and the sum of their numerators can be expressed from (21) and the definition of $\beta = \ln 10/5\alpha$ as:

$$\begin{aligned} \Gamma &= 100G\left(L_{max,C}(n_C)\right) n_C \\ &+ 10 f_{LC}\left(L_{max,C}(n_C)\right) \ln 10 \left(C^* - \frac{2n_C}{\alpha}\right) \end{aligned} \quad (23)$$

In (23), the first term is positive and α is the path loss exponent, which depends on the environment and is always higher or equal than 2, as discussed in Section II. Consequently, since $n_C \leq C^*$, the second term is also positive and therefore $\phi''(n_C) > 0$, which proves the proposition. ■

Theorem 2: If $B(n_{Cmin}) < 0$, the position of the minimum of the function $\phi(n_C)$ in the range $[n_{Cmin}, n_{Cmax}]$ is given as follows:
(a) If $B(n_{Cmin}) \geq A(n_{Cmin})$ the minimum occurs at $n_C^{opt} = n_{Cmin}$.
(b) If $B(n_{Cmin}) < A(n_{Cmin})$, the minimum occurs at n_{Cmax} if $B(n_{Cmax}) \leq A(n_{Cmax})$ or at a value n_C^{opt} in the range $n_{Cmin} < n_C^{opt} < n_{Cmax}$ if $B(n_{Cmax}) > A(n_{Cmax})$.

Proof: According to Proposition 3, if $\phi'(n_{Cmin}) = B(n_{Cmin}) - A(n_{Cmin}) \geq 0$, or equivalently $B(n_{Cmin}) \geq A(n_{Cmin})$, this means that $\phi'(n_C) \geq 0$ in all the range and therefore either there will not exist any critical point or it will exist in $n^* = n_{Cmin}$. Consequently, the minimum of $\phi(n_C)$ will be in n_{Cmin}. This proves the statement (a) of the theorem. In turn, if $\phi'(n_{Cmin}) = B(n_{Cmin}) - A(n_{Cmin}) < 0$, or equivalently $B(n_{Cmin}) < A(n_{Cmin})$, because of Proposition 3, there will exist a unique critical point $n^* > n_{Cmin}$ fulfilling $\phi'(n^*) = 0$. Then, if $n^* \geq n_{Cmax}$, which is equivalent from proposition 3 to $\phi'(n_{Cmax}) = B(n_{Cmax}) - A(n_{Cmax}) \leq 0$, that is $B(n_{Cmax}) \leq A(n_{Cmax})$, the minimum of the function will be in n_{Cmax} and otherwise it will be in the range $n_{Cmin} < n_C^{opt} < n_{Cmax}$. This proves the statement (b) of the theorem. ■

Table I summarizes the different optimal allocation conditions derived from Theorems 1 and 2 depending on the functions $B(n_C)$ and $A(n_C)$. With respect to the physical meaning of Theorem 1, notice that the condition $B(n_{Cmin}) \geq 0$ is equivalent to $F_{LT}\left(L_{max,T}\right) \geq F_{LC}\left(L_{max,C}(n_{Cmin})\right)$, which means that in this case the TDMA technology has always a lower outage than the CDMA technology no matter the number of users allocated in CDMA. Therefore, the optimum policy is to allocate all the users in TDMA up to its maximum capacity and the remaining users, if any, $\max(0, U - C_T) = n_{Cmin}$, in the CDMA technology. It is also worth mentioning that the reverse situation $B(n_C) < 0$ in all the range, i.e. $F_{LT}\left(L_{max,T}\right) < F_{LC}\left(L_{max,C}(n_{Cmax})\right)$, which means that CDMA always provides lower outage than TDMA, does not necessarily lead to an optimal allocation consisting in allocating all the users in CDMA, as derived from Theorem 2.

IV. RESULTS

In the following four representative case studies are analyzed in order to show the optimization results and how the functions $A(n_C)$ and $B(n_C)$ are able to capture the specificities of each access technology depending on the scenario. Common parameters to all the case studies are $C_T = 23$, $W = 3.84$ Mchips/s, $P_{N,C} = -104$ dBm. Furthermore, the same parameters $L_0 = 128.1$ dB, $\alpha = 3.76$, $\sigma = 10$ dB in the propagation model are considered for the TDMA and CDMA technologies, assuming that their frequency bands are close enough to consider that approximately the same propagation conditions apply. Table II presents the results obtained in terms of the optimum allocation (n_C^{opt},n_T^{opt}) and outage probability for each case study. For comparison purposes, the allocation strategies in which the maximum number of users are allocated in CDMA (i.e. $n_C = n_{Cmax}$) and in which the maximum number of users are allocated in TDMA (i.e. $n_C = n_{Cmin}$) are also presented.

Case 1 represents a typical voice service with bit rate $R_b = 12.2$ kb/s. The cell radius is assumed to be $R = 900$ m and the maximum transmit power levels are $P_{max,T} = 33$ dBm and $P_{max,C} = 21$ dBm. The sensitivity for TDMA is $P_{S,T} = -108$ dBm and for CDMA the E_b/N_0 target is 9.5 dB. The resulting maximum CDMA capacity is $C_C = 36$. A total of $U = 40$ users are considered. For this case it can be obtained that $n_{Cmin} = 17$, and $B(n_{Cmin}) = 0.0232$, so according to Theorem 1 the optimum policy results in allocating the maximum number of users in TDMA, i.e. $n_C^{opt} = n_{Cmin} = 17$. A very significant outage probability reduction is obtained with respect to the allocation of the maximum number of users in CDMA.

In turn, Case 2 is equivalent to Case 1 but with E_b/N_0 target $= 6$ dB, representing that some physical layer techniques (e.g. reception diversity, a different coding scheme, etc.) are used to improve CDMA performance, so that the resulting maximum CDMA capacity is $C_C = 80$. In this case, $n_{Cmin} = 17$ and $n_{Cmax} = 40$, leading to $B(n_{Cmin}) = -0.00938$, $B(n_{Cmax}) = -1.53 \cdot 10^{-4}$, $A(n_{Cmin}) = -0.00453$ and $A(n_{Cmax}) = -0.0242$. Consequently, $B(n_{Cmin}) < A(n_{Cmin})$ and $B(n_{Cmax}) > A(n_{Cmax})$, which from Theorem 2 leads to the optimum existing in an intermediate value found to be $n_C^{opt} = 23$, as shown in Table II.

Case 3 is an example of a situation where the optimum allocation corresponds to allocating all the users in CDMA. The conditions are the same as in Case 2 but a lower number of users $U = 20$ is considered. For this case, $n_{Cmax} = 20$ and $n_{Cmin} = 0$, and it can be found that $B(n_{Cmin}) = -0.0130$, $B(n_{Cmax}) = -0.00854$, $A(n_{Cmin}) = 0$ and $A(n_{Cmax}) = -0.00582$. Consequently, according to Theorem 2 the optimum is in n_{Cmax}, reflecting that for this lower number of users the interference existing in CDMA is low and therefore it is convenient to allocate all the traffic in CDMA.

Finally, Case 4 considers a data service with bit rate $R_b = 64$ kb/s that can be allocated to either the TDMA or the CDMA system. The cell radius is reduced to $R = 400$m and the maximum transmit power levels are $P_{max,T} = 36$ dBm and $P_{max,C} = 24$ dBm, representing that a terminal for data transmission may have more power available than a voice terminal. For CDMA the requirements are E_b/N_0 target= 6 dB and for TDMA the sensitivity is $P_{S,T} = -85$ dBm. The resulting maximum CDMA capacity is $C_C = 16$. A total of $U = 20$ users are considered. In this case $n_{Cmax} = 16$ and $n_{Cmin} = 0$, and it can be found from the computation of $B(n_C)$ and $A(n_C)$ functions that $B(n_{Cmin}) = -0.0920$, $B(n_{Cmax}) = 0.0852$, $A(n_{Cmin}) = 0$ and $A(n_{Cmax}) = -22.54$. Consequently, from Theorem 2, the optimum is located in an intermediate value $n_C^{opt} = 14$, as shown in Table II. Notice that significant outage reductions can be achieved with this optimum allocation with respect to the other alternatives.

V. Conclusions

This paper has demonstrated the optimum traffic allocation in heterogeneous CDMA and TDMA scenarios minimizing the total outage probability in the uplink. The mathematical framework developed here has allowed capturing the relevant radio access parameters influencing on the optimal allocation by means of analytical functions. The proposed methodology establishes a useful reference for the development of practical CRRM algorithms.

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