Uplink Capacity Investigations of TDD/CDMA

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***Abstract*—In this contribution we analyze the uplink capacity of a TDD-/CDMA system. In TDD/CDMA the mobiles suffer from interference inflicted by the other mobile stations (MSs) both in the reference cell the MS is roaming in (intracell interference) as well as due to those in the neighbouring cells (intercell interference). Furthermore, in contrast to FDD/CDMA, where the Base Stations (BSs) transmit in an orthogonal frequency band, in TDD/CDMA there is additional interference imposed by other BSs of the adjacent cells. In return for this disadvantage TDD/-CDMA guarantees the flexible utilization of all the available bandwidth, which meets the demand for the support of asymmetric uplink and downlink services, such as high speed data rate download in mobile Internet services, etc. This study quantifies the amount of uplink interference inflicted by the MSs and BSs. With the aid of characterising the interference, a detailed discussion of the uplink capacity of TDD/CDMA is provided and two extreme teletraffic loading scenarios of the UTRA TDD/CDMA system are considered. Our numerical results show that the capacity of TDD/CDMA is significantly poorer, than that of FDD/CDMA.**

I. INTRODUCTION

The third generation mobile communication systems such as the Universal Mobile Telecommunication System [1] (UMTS) have been designed for supporting various types of services, such as video telephony [2], fax, wireless Internet, etc. All these services require flexible and efficient resource allocation methods. The IMT-2000 standard comprises two types of air-interfaces, namely FDD/CDMA and TDD/CDMA [2]. In the latter scheme, the uplink and downlink transmissions are time multiplexed on different timeslots of the same carrier, while in FDD/CDMA the uplink and downlink transmissions occur in different frequency bands [1, 3–6]. The advantage of TDD/CDMA is that it is capable of accommodating diverse asymmetric and variable-rate services, such as multimedia applications, Internet browsing and file transfer, etc [7–9], by assigning different number of timeslots in the up and downlinks. A further benefit of TDD/CDMA is the similar nature of the channel in the uplink and downlink, since the corresponding burst are transmitted at the same frequency. This can be advantageously exploited for open loop power control and transmission diversity assisted pre-RAKE techniques [9], which can reduce the complexity of the MS. Furthermore, adaptive antennas or beam forming as well as multiuser detection are more likely to be implemented in TDD/CDMA cellular scenarios, since on average the number of active MSs in every slot is reduced, which reduces the complexity. The employment of beam forming may lead to a further increased system capacity. In recent years research interests in the evaluation of the capacity of FDD/CDMA systems have intensified. By contrast, there is a paucity of contributions on the capacity analysis of TDD/CDMA in cellular environments. Hence in this contribution we analyse the capacity of TDD/CDMA cellular systems.

The rest of the paper is organised as follows. The interference scenario considered is presented in Section 2, which is followed by the analysis of the uplink capacity of the TDD/CDMA system in Section 3. The proposed technique can also be appropriately modified for considering the downlink. In Section 4 we provide numerical results for characterising the various interference scenarios and the system capacity of TDD/CDMA is compared to that of FDD/CDMA. Before concluding, in Section 5 we study two extreme teletraffic loading scenarios in the context of the UTRA system. Finally, we conclude our discussions in Section 6.

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II. INTERFERENCE SCENARIO IN TDD/CDMA

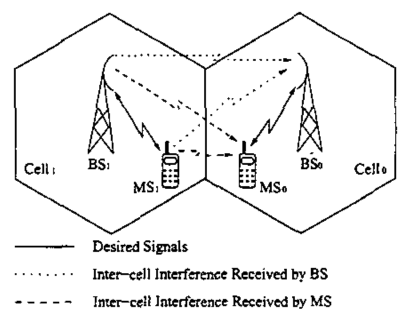

Fig. 1. Inter-cell interference.

TDD is attractive in terms of facilitating the allocation of asymmetric or uneven resources to the uplink and downlink, which supports a more efficient exploitation of the frequency bands available. However, the associated interference scenario is markedly different from that experienced in FDD, as shown in Figure 1.

Mobile to mobile (MS-to-MS) interference occurs in the situation displayed in Figure 1, if MS_1 is transmitting, while MS_0 is receiving in a specific timeslot mapped to the same carrier frequency in an adjacent cell. The MS-to-MS interference cannot be completely avoided by network planning, since the location of mobiles cannot be controlled.

TDD/CDMA is also prone to base station (BS-to-BS) interference. In fact, as it will be shown later, it is the most serious source of intercell interference in a TDD/CDMA cellular scenario. As seen in Figure 1, if BS_1 is transmitting and BS_0 is receiving at the same time in a given timeslot, BS-to-BS interference takes place, provided that these base stations are in adjacent cells. The severity of the BS-to-BS interference depends heavily on the path loss between the two base stations, hence it can be reduced with the aid of careful network planning. In the next section we present our system model used in the analysis.

III. CAPACITY ANALYSIS

A. Interference Model

In this contribution we stipulate the simplifying assumption that all the mobile users in a cell are synchronous, hence they all may transmit or receive in any given timeslot. The reason behind this simplifying assumption is that MSs roaming in the same cell may seriously interfere with each other, if they are asynchronous. This is particularly so, when their locations are near to each other. By contrast, the mobile users belonging to the neighbouring cells may receive or transmit at any given time asynchronously with respect to the serving cell due to the asynchronous nature of the adjacent cells. The adjacent cells may also use an asymmetric uplink/downlink loading of the carriers. The associated details can be explicitly viewed in Figure 2.

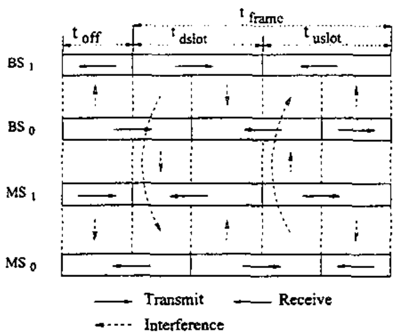

Fig. 2. Frame structure of TDD/CDMA.

As shown in Figure 2, each cell has the same fixed frame duration, which are divided into uplink (UL) slots and downlink (DL) slots. In other words, only the situation of having one switch point between the UL/DL slots of a frame is considered in this contribution. Again, the different traffic cells' frames are transmitted asynchronously and the time offset between them is denoted by t_{off}, which can be normalised by the frame duration t_{frame}, yielding the relative time-offset of $\alpha = \frac{t_{off}}{t_{frame}}$. Initially we assume that all the time frames in the cells are equally divided into uplink slots and downlink slots, which implicitly assumes that neighbouring cells have the same half/half UL/DL pattern. At a later stage, the analysis of the asymmetric division between the downlink and uplink sections of the frame can be readily accomplished by following a similar approach to that developed for the equal division of time frames, as it will be shown in Section 5.

B. Interference Analysis

Before commencing our interference analysis we stipulate our assumptions. Firstly, since the downlink and uplink use the same frequency bands, we assume that they experience identical attenuations. These attenuations depend on the distance between the BS and MS, as well as on the shadow-fading expressed as $10^{\frac{\xi}{10}}$, where ξ is a Gaussian random variable having a standard deviation of $\sigma = 8$ dB and a zero mean. We assume furthermore that the fast fading does not affect the average power level. Secondly, we assume that both the transmitter and receiver require the same SIR for achieving a given BER performance. Considering the effects of channel coding and diversity is beyond the scope of this contribution, since they do not affect the validity of our analysis. We also assume that each cell has the same number of users, who are uniformly distributed over the geographic area of the cells. Hard handoffs are assumed. Mobile users may encounter problems during the process of handoff, when they travel across cell boundaries, where these two cells' transmitted frames are asynchronous. Our investigations were simplified by assuming that there are always free timeslot carrier combinations for facilitating handoffs.

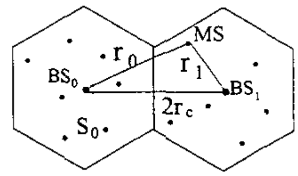

Fig. 3. Uplink geometry.

Let us now commence our analysis of the uplink interference characterisation of TDD/CDMA. We assume that there are M active MSs uniformly distributed in each cell. We normalise the cell radius to unity, which is denoted by r_c in this contribution. Then simple hexagonal geometry dictates that we have $\rho = \frac{2M}{3\sqrt{3}} \frac{\text{users}}{\text{unit area}}$, which represents the density of MSs in each cell. Perfect power control is assumed, which implies that each MS's signal arrives at the serving BS at an identical average power level of p_{ms}. Then the E_b/N_0 can be expressed as:

$$\frac{E_b}{I_0} = \frac{\frac{W}{R}}{\frac{I_{intra}}{p_{ms}} + \frac{I_{inter}}{p_{ms}} + \frac{N_0 W}{p_{ms}}}, \tag{1}$$

where E_b and I_0 are bit energy and interference power density, respectively, while I_{intra} stands for the interference generated by the MSs in the serving cell (intracell interference). Futhermore I_{inter} represents the interference due to the MSs and BSs in the neighbouring cells (intercell interference). In this investigation we only consider the intercell interference due to the first tier of surrounding cells. Finally, N_0W represents the Gaussian noise power at the serving BS, while W is the signals' bandwidth and the information data rate is fixed at R. Furthermore, we have:

$$I_{intra} = \sum_{i=2}^{M} v_i \cdot p_{ms}, \tag{2}$$

while v_i is the voice activity factor, $v_i = 1$ with probability γ and $v_i = 0$ with probability $1 - \gamma$. A typical value of γ is $\frac{3}{8}$ [3]. Let us assume that each MS has the same voice activity of v_i, so that we can simply use v for representing the voice activity factor. The intercell interference is not only due to the MSs, but also due to the BSs in the adjacent cells. Hence we have:

$$I_{inter} = I_{inter\_ms} + I_{inter\_bs} = \sum_{j=1}^{6} \Bigg\{ \text{Prob}\left(\alpha_j \le \frac{1}{2}\right) \cdot \left[\sum_{i=1}^{M} v\left(1 - 2\alpha_j\right) I_{ms\_ij} + \sum_{j=1}^{6} v 2\alpha_j I_{bs\_j}\right] + \text{Prob}\left(\alpha_j > \frac{1}{2}\right) \cdot \left[\sum_{i=1}^{M} v\left(2\alpha_j - 1\right) I_{ms\_ij} + \sum_{j=1}^{6} v\left(2 - 2\alpha_j\right) I_{bs\_j}\right] \Bigg\}, \tag{3}$$

where $\alpha_j = \frac{t_{off}}{t_{frame}}$ is the relative time offset between the jth interfering cell's transmitted frame and the designed cell's transmitted frame. Furthermore, I_{ms_ij} denotes the interference inflicted by the ith MS in the jth cell in the first tier of interfering cells. Since all the cells are asynchronous, consequently α_j in each cell is independent of the relative time offsets of the other cells and we assume that α_j is uniformly distributed in $[0, 1]$. Additionally, the relative time offsets α_j are independent of each other, and they have identical first and second moments given by $E(\alpha)$ and $E(\alpha^2)$, respectively. If we define $\alpha_j' = 1 - \alpha_j$ when $\alpha_j > \frac{1}{2}$, obviously α and α' have an identical distribution. As a consequence, Equation (3) can be simplified to:

$$I_{inter} = \sum_{j=1}^{6} \left[\sum_{i=1}^{M} v \cdot (1 - 2\alpha_j) \cdot I_{ms\_ij} + v \cdot 2\alpha_j \cdot I_{bs\_j} \right], \quad \left(0 \le \alpha_j \le \frac{1}{2}\right). \quad (4)$$

To elaborate further, we let the distance of the MS positioned at the coordinates (x, y) from the given cell's BS be $r_0(x, y)$, while that with respect to the interfering cell's BS be $r_1(x, y)$, as shown in Figure 3. Correspondingly we use α_1 for representing the relative frame offset between the serving cellsite BS_0 and the interfering basestation BS_1, as shown in Figure 3. The MS at the coordinates (x, y) is likely to be communicating with the nearest BS, namely BS_1, which provides the highest received pilot signal strength for the MS from the set of pilots reaching the MS in the ideal hard handoff situation. As mentioned before, the propagation path loss is generally modeled as the product of the mth power of the distance, while an additional log-normally distributed factor represents the slowly varying shadowing losses. Hence, for a MS at a distance r from a BS the attenuation is proportional to $r^m 10^{\frac{\xi}{10}}$, where typically we have $m = 4$.

We can now express the total relative interference at the serving cell's BS due to all users in all other surrounding first-tier cells, which is denoted as region $\overline{S_0}$ in Figure 3 corresponding to the total area excluding the central reference cell, which is formulated as:

$$\frac{I_{inter\_ms}}{p_{ms}} = \iint_{\overline{S_0}} v(1 - 2\alpha_1) \cdot \frac{r_1^m(x, y) \cdot 10^{\frac{\xi_1}{10}}}{r_0^m(x, y) \cdot 10^{\frac{\xi_0}{10}}} \cdot \psi(r_0, r_1, \xi_0, \xi_1)\, \rho \mathrm{d}x\mathrm{d}y, \quad (5)$$

where, $\psi(r_0, r_1, \xi_0, \xi_1) = \begin{cases} 1 & \text{if } \left(\frac{r_1}{r_0}\right)^m \cdot 10^{(\xi_1 - \xi_0)/10} \le 1 \\ 0 & \text{otherwise} \end{cases}$.

The above constraint imposed on $\psi(\cdot)$ indicates that under the assumption of perfect hard handoff the MS' power is controlled by that specific BS, which has the highest pilot signal strength from the set of all the pilots reaching this MS. In our further discourse we simplify the notation $r_0(x, y)$, $r_1(x, y)$ to r_0, r_1, respectively. If we define the constant $\beta = \frac{\ln 10}{10}$, then we have:

$$E\left(\frac{I_{inter\_ms}}{p_{ms}}\right) = E(v)(1 - E(2\alpha)) \cdot \exp\left((\beta\sigma)^2\right) \cdot \iint_{\overline{S_0}} \left(\frac{r_1}{r_0}\right)^m \left[1 - \mathrm{Q}\left(\frac{m}{\sqrt{2}\beta\sigma} \log\left(\frac{r_0}{r_1}\right) - \sqrt{2}\beta\sigma\right)\right] \rho \mathrm{d}x\mathrm{d}y, \quad (6)$$

where $\mathrm{Q}(\cdot)$ is the standard Q-function. Furthermore, under the assumption that we know the second order statistics of ξ_0 and ξ_1, we developed a formula for the variance of the random variable $\frac{I_{inter\_ms}}{p_{ms}}$, which is given by:

$$\mathrm{Var}\left(\frac{I_{inter\_ms}}{p_{ms}}\right) = \iint_{\overline{S_0}} \left(\frac{r_1}{r_0}\right)^{2m} \Big\{ E(v^2) E\left((1 - 2\alpha)^2\right) \exp\left((2\beta\sigma)^2\right) \cdot \left[1 - \mathrm{Q}\left(\frac{m}{\sqrt{2}\beta\sigma} \ln\left(\frac{r_0}{r_1}\right) - 2\sqrt{2}\beta\sigma\right)\right] - \Big\{ E(v) E(1 - 2\alpha) \exp\left((\beta\sigma)^2\right) \cdot \left[1 - \mathrm{Q}\left(\frac{m}{\sqrt{2}\beta\sigma} \ln\left(\frac{r_0}{r_1}\right)\right) - \sqrt{2}\beta\sigma\right] \Big\}^2 \Big\} \cdot \rho \mathrm{d}x\mathrm{d}y. \quad (7)$$

In this contribution, we assume that the BS' transmission power is not fixed, but it is adjusted on the basis of the attenuations experienced by the MSs served by the BS. More specifically, we adjust the BS' power based on our previous assumption that both the uplink and downlink experience the same attenuation and that both the MS and the BS require the same SIR for facilitating an identical BER performance. Hence the BS' transmission power used for a particular MS is also proportional to the attenuation between the MS and the BS. In other words, the BS' total transmission power is given by the sum of transmission powers of its MSs served. We also assume that the sum of the transmit powers of the MSs does not exceed the BS' maximum transmitter power.

Since we assume that the MSs are typically uniformly distributed in each cell, the total relative interference at the serving cell's BS due to all other BSs located in the surrounding first-tier cells can be expressed as:

$$\frac{I_{inter\_bs}}{p_{ms}} = \iint_{\overline{S_0}} v \cdot 2\alpha_1 \cdot \frac{r_1^m(x, y) \cdot 10^{\frac{\xi_1}{10}}}{(2r_c)^m \cdot 10^{\frac{\xi_b}{10}}} \cdot \psi(r_0, r_1, \xi_0, \xi_1)\, \rho \mathrm{d}x\mathrm{d}y, \quad (8)$$

where $\psi(\cdot)$ is defined as in Equation (5). The numerator in the integral represents that specific fraction of the interfering BS' transmission gain, which is proportional to the path loss plus shadowing-related attenuation between the BS and the MS. By contrast, the denominator represents the path loss plus shadowing-related attenuation between two BSs. We are now in the position to express the average relative interference at the serving cell's BS due to all other BSs in the surrounding first-tier cells, which is given by:

$$E\left(\frac{I_{inter\_bs}}{p_{ms}}\right) = E(v) E(2\alpha) \frac{\exp\left((\beta\sigma)^2\right)}{(2r_c)^m} \cdot \iint_{\overline{S_0}} r_1^m(x, y) \left[1 - \mathrm{Q}\left(\frac{m}{\sqrt{2}\beta\sigma} \ln\left(\frac{r_0}{r_1}\right)\right)\right] \rho \mathrm{d}x\mathrm{d}y. \quad (9)$$

Similarly, we can obtain the variance of the random variable $\frac{I_{inter\_bs}}{p_{ms}}$ as:

$$\mathrm{Var}\left(\frac{I_{inter\_bs}}{p_{ms}}\right) = \iint_{\overline{S_0}} \Big\{ E(v^2) E\left((2\alpha)^2\right) \exp\left((2\beta\sigma)^2\right) \cdot \left[1 - \mathrm{Q}\left(\frac{m}{\sqrt{2}\beta\sigma} \ln\left(\frac{r_0}{r_1}\right)\right)\right] - \Big\{ E(v) E(2\alpha) \exp\left((\beta\sigma)^2\right) \cdot \left[1 - \mathrm{Q}\left(\frac{m}{\sqrt{2}\beta\sigma} \ln\left(\frac{r_0}{r_1}\right)\right)\right] \Big\}^2 \Big\} \cdot \left(\frac{r_1}{2}\right)^{2m} \cdot \rho \mathrm{d}x\mathrm{d}y. \quad (10)$$

	$E\left[\frac{I_{inter\_ms}}{I_{intra}}\right]$	$E\left[\frac{I_{inter\_bs}}{I_{intra}}\right]$	f	$Var\left[\frac{I_{inter}}{I_{intra}}\right]$
FDD	0.27 [3]	0	0.27	0.078
TDD	0.135	1.187	1.322	1.908

TABLE I

INTERFERENCE AND RELATIVE INTERFERENCE FACTORS IN FDD/CDMA AND TDD/CDMA. THE PATH LOSS EXPONENT WAS $m = 4$ AND THE SLOW-FADING STANDARD DEVIATION WAS $\sigma = 8$DB

C. Capacity analysis

Now with the knowledge of the statistics of the random variable $\frac{I_{inter\_ms}}{P_{ms}}$ and $\frac{I_{inter\_ms}}{P_{ms}}$, the Gaussian approximation method developed for example in [3] can be employed. Hence we are in the position to quantify the capacity of a TDD/CDMA cellular scenario.

For the sake of rendering the results comparable, we use the same parameters as in [3]. Accordingly, the speech rate was set to 8kb/s when communicating over a channel having a total bandwidth of 1.25MHz. In order to achieve the required BER performance of BER $< 10^{-3}$ on the UL, the minimum bit energy to noise ratio (E_b/I_0) was set to 7dB. With the aid of Equation (16) in [3], we can quantify the BER performance of a TDD/CDMA scenario, which is shown later in Figure 4.

IV. Numerical Results

If we define $f = E\left[\frac{I_{inter}}{I_{intra}}\right]$, by combining Equations (1), (2), (5) and (8), we are in the position to explicitly compare the intercell interference behaviour of TDD/CDMA and FDD/CDMA. The corresponding numerical results are shown in Table I.

It can be inferred from Table I that in TDD/CDMA the interference imposed by the first-tier neighbouring cells is severe and hence it dramatically degrades the system capacity. The above results were obtained on the basis of the assumption that the time frame transmission instants of each cell are independent and that all the UL/DL timeslot allocation patterns are the same for every cell, namely 50%.

It can also be inferred from Figure 4 that a TDD/CDMA system is capable of supporting 9 MSs in each cell.By contrast, FDD/CDMA is capable of supporting 31 MSs, while maintaining an adequate performance under the same conditions. If the load of the neighbouring cells is reduced from 9 to 6 MSs in TDD/CDMA, the reference base station becomes capable of serving 22 MSs. Furthermore, it can be inferred from Figure 4 that the reduction of the neighbouring cells' interference load to a quarter of that in the reference cell leads to a higher relative user capacity improvement in a TDD/CDMA system compared to that in a FDD/CDMA system. Specifically, the relative user capacity improvements are $\frac{22-9}{9} \approx 144\%$ and $\frac{45-31}{31} \approx 45\%$, respectively.

V. Asymmetric Traffic

In our previous discourse we simplified the UL/DL TDD/CDMA frame allocation by fixing the UL/DL slot boundary in each time frame. More specifically, every time frame was equally divided into a downlink and uplink segment. Let us now consider a more complex scenario by randomly varying the UL/DL segment switch points in each time frame. Furthermore, we assume that every UL/DL segment switch point would remain fixed during the period of observation, and that the neighbouring cells have an identical UL/DL timeslot allocation pattern.

With the aid of Figure 5 we can readily summarise all the possible interference patterns by varying α and ζ, as shown in Table II, where

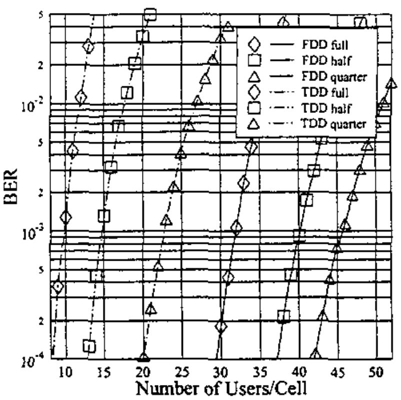

Fig. 4. BER versus the number of users/cell served in the UL of TDD/CDMA compared to that of FDD/CDMA, these results were generated with the aid of Equation (1), (6), (7), (9), (10).

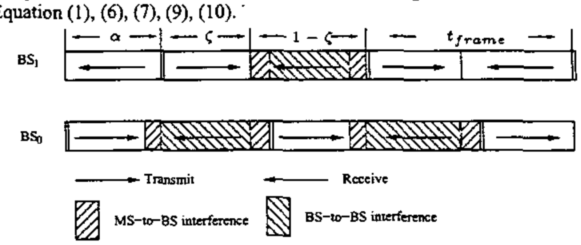

Fig. 5. Interference under the variable switch point

$\alpha = \frac{t_{offset}}{t_{frame}}$ is the normalised frame offset, as defined before, while ζ is the normalised downlink segment duration. Hence $1-\zeta$ is the normalised uplink segment duration. It can be inferred from Table II that the amount of interference endured by the serving BS can be controlled by varying α and ζ. We assume that both α and ζ are uniformly distributed in $[0,1]$. Then we can average the amount of interference inflicted by the BSs and MSs for the various values of the random variables α and ζ as follows. First we consider the interference generated by the BSs, yielding:

$$\begin{aligned} \mathrm{E}[\alpha,\zeta] = \mathrm{E}\Big\{ & \Pr\left(\zeta > \tfrac{1}{2}\right) \cdot \\ & \left[\int_0^{\zeta} \frac{\alpha}{1-\zeta} d\alpha + \int_{\zeta}^{1-\zeta} \frac{\zeta}{1-\zeta} d\alpha + \int_{1-\zeta}^{1} \frac{1-\alpha}{1-\zeta} d\alpha\right] + \\ & \Pr\left(\zeta \le \tfrac{1}{2}\right) \cdot \left[\int_0^{1-\zeta} \tfrac{\alpha}{1-\zeta} d\alpha + \int_{1-\zeta}^{\zeta} d\alpha + \int_{\zeta}^{1} \tfrac{1-\alpha}{1-\zeta} d\alpha\right]\Big\} \\ & = \mathrm{E}[\zeta]. \end{aligned} \quad (11)$$

The inner part of the expectation operation in the $[\cdot]$ bracket represents the averaging over the random variable α, while the expectation operation $\mathrm{E}[\cdot]$ corresponds to the averaging over the random variable ζ.

The average interference inflicted by the MSs is given by $1-\mathrm{E}[\zeta]$. By comparing the results in Equation (11) with the corresponding part in Equation (9) and (6) we observe that these results are the same as those when we equally divided the time frame into uplink and downlink slots. The reason behind this is that we assumed that ζ is uniformly distributed over the interval of $[0,1]$.

		$BS \rightarrow BS$:	$MS \rightarrow BS$:
$\alpha < \frac{1}{2}$	$1-\zeta < \alpha < 1-\alpha$	$1-\zeta$	0
	$1-\alpha > 1-\zeta > \alpha$	α	$1-\zeta-\alpha$
	$1-\zeta > 1-\alpha > \alpha$	ζ	$1-2\zeta$
$\alpha > \frac{1}{2}$	$1-\zeta < 1-\alpha < \alpha$	$1-\zeta$	0
	$\alpha > 1-\zeta > 1-\alpha$	$1-\alpha$	$\alpha-\zeta$
	$1-\zeta > \alpha > 1-\alpha$	ζ	$1-2\zeta$

TABLE II

RELATIVE INTERFERENCE INFLICTED BY NEIGHBOURING BSS AND MSS IN TDD/CDMA CELLULAR SCENARIO.

Let us now briefly discuss two extreme cases. In UTRA TDD/-CDMA there are 15 slots within each $10ms$ frame. There can be multiple UL/DL segment switch points or a single switch point in each frame. However, there has to be at least one slot allocated to both the uplink and the downlink. Now we are in the position to quantify the intercell interference in two extreme situations in the context of the UTRA TDD/CDMA scenario; namely when using one uplink slot and 14 downlink slots (Scenario 1) as well as for 14 uplink slots and one downlink slot (Scenario 2). With the aid of Equation (11) we can obtain the first and second moment of the average intercell BS-to-BS interference in Scenario 1 as: $\mathrm{E}\left[\alpha, \frac{14}{15}\right] = \frac{14}{15}$ and $\mathrm{E}\left[\left(\alpha, \frac{14}{15}\right)^2\right] = \frac{41}{45}$, respectively.

In the same way, we can also have the first and second moment of average interference inflicted by MSs in adjacent cells. Similarly, we can also express the corresponding results for the second scenario.

By replacing the terms $\mathrm{E}(2\alpha)$ and $\mathrm{E}\left((2\alpha)^2\right)$ with $\mathrm{E}\left[\alpha, \frac{14}{15}\right]$ and $\mathrm{E}\left[\left(\alpha, \frac{14}{15}\right)^2\right]$ in Equations (6), (7), (9) and (10) we obtain the intercell interference of the above extreme cases. Consequently, we are in the position to evaluate the corresponding capacity, which is shown in Figure 6.

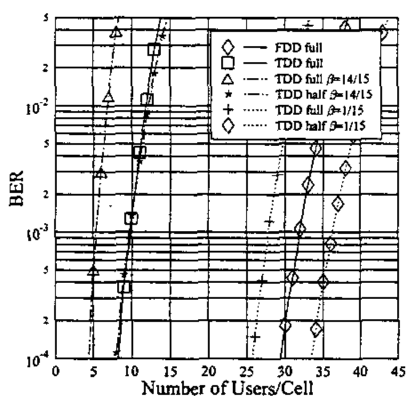

Fig. 6. BER versus the number of users/cell served in the UL for the two extreme cases considered in the context of the UTRA TDD/CDMA protocol, these results were generated with the aid of Equation (1), (6), (7), (9), (10).

Explicitly, Figure 6 suggests that the capacity of the above two extreme cases is worse than that of TDD/CDMA using a 50% UL/DL segment as well as that of FDD/CDMA. In Scenario 1, the capacity of the reference cell increases from 5 to 9 MSs, when the load of the neighboring cells expressed in terms of the number of MSs is reduced to half. Under the same circumstances, in Scenario 2, the capacity increases from 27 to 36 MSs. The relative increases are 80% and 33.3%, respectively.

VI. CONCLUSION

TDD/CDMA constitutes a flexible resource allocation scheme. It also supports the employment of low complexity multiuser detection, beam forming, fast open loop power control and pre-RAKE techniques, which results in reducing the system's complexity and size. The cost of all of these benefits is the extra intercell interference introduced into system, which degrades the system capacity. Figure 4 and 6 characterise the uplink BER versus the number of MSs supported in a TDD/CDMA cellular environment.

It can be inferred from these graphs that the intercell interference, especially the intercell BS-to-BS interference substantially decreases the system's user capacity. Hence we can increase the total system capacity by reducing the BS-to-BS interference. This can be achieved with the aid of a higher than unity frequency reuse factor, since the BS-to-BS interference reduces as the distance between the BSs operating at the same frequency increases due to using a multi-cell cluster. Another way of achieving a reduced BS-to-BS interference is beam forming, since the BS can focus its transmitted signal energy on the MSs, while creating a null in the direction of the adjacent BSs. However, this can be only achieved, if there are no MSs roaming in the vicinity of the line between the BS and the neighbouring BS. The performance of the adaptive antenna assisted and adaptive modulation aided UTRA FDD system was characerised in [1,5,6].

Our further investigations demonstrated that the user capacity can be increased upon employing a frequency reuse factor of 3, which increases the effective capacity from 9 to 14. Higher frequency reuse factors would further reduce the BS-to-BS interference, but at the cost of reducing the effective user capacity.

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