

# Forward Link Performance of TDMA/W-CDMA Spectrum Overlaid System with Interference Cancellation for Future Wireless Communications\*

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**SUMMARY** In this paper, the co-existence of TDMA and W-CDMA spectrum sharing system (TDMA/W-CDMA overlaid system) with cellular architecture is discussed. In this system, both systems share the same frequency band to improve the spectrum efficiency. Overall rate, bit error ratio (BER) and spectrum efficiency of the system are calculated for the forward link (down-link) in the presence of AWGN channel. Taking into account the path loss and shadow fading loss in this system with cellular architecture, W-CDMA applying interference cancellation (IC) shows a substantial difference in spectrum efficiency, the overlaid system can provide a greater overall rate and higher spectrum efficiency than a single multiple access-based system such as TDMA system or W-CDMA system. The interference cancellation can significantly improve BER of the spectrum overlaid system.

**key words:** *code-division multiple access (CDMA), time-division multiple access (TDMA), TDMA/W-CDMA overlaid system, notch filter, signal clipper*

## 1. Introduction

With the expected wireless revolution in telecommunications [1], [2], the available spectrum should be used efficiently and flexibly [3], [4]. One step in this direction is the use of spread spectrum overlay. In the overlaid systems, it is significant to adopt some advanced signal processing and interference cancellation techniques, such as notch filter and signal clipper. When W-CDMA is considered as a wireless access technique for *IMT2000* systems to provide multimedia service including voice, interactive data, file transfer, internet access, images and facsimiles, the architecture of TDMA/W-CDMA sharing the same bandwidth will become an important topic. In order to efficiently make use of a radio spectrum allocated to an operator that

is limited by a regulatory body, the adoption of this overlaid system may have many attractions.

In fact, the concept of spectrum overlay of a new system to the existing system is not strange but has been studied in Refs. [2]–[4] near a decade ago. Although in Ref. [2] the overlay consideration has been proposed and the interference rejection schemes were described, the investigations were focused on BER that is expressed directly as the function of bit energy-to-noise density ratio and interference power-to-signal power ratio. Then the practical overlaid systems such as CDMA/FDMA [5], CDMA/TDMA [8], [13] or N-CDMA/W-CDMA [6]–[8], were not considered. It is only as a simplistic example for overlay consideration. In Ref. [3], it only considered a single cell system, the interference from adjacent cells is neglected. The system is operating over a frequency non-selective, Rayleigh fading channel. Reference [4] investigated the cellular structure, but it adopted very simply method to calculate the interference generated from surrounding cells and only system capacity and cumulative probability of the power received were investigated with only 3 channels/sector in GSM system.

Recently, with the rapidly increasing of mobile users, how to use the limited spectrum more flexible and the development of physical overlaid systems become an important problem. Many researchers focused their attention on this and considered various types of practical applications, such as Refs. [5]–[8]. However, the forward link performance in TDMA/W-CDMA spectrum overlaid system employing the notch filter and the signal clipper to decrease the multi-interference has not been investigated until now. In Ref. [5], the overlaid system of cellular CDMA on AMPS was analyzed, but the analog mobile system has been given up in the world. References [6] and [7] employed a simple model for N-CDMA/W-CDMA spectrum overlaid system and only investigated the system capacity tradeoff between the N-CDMA system and W-CDMA system. Reference [8] investigated the situation of TDMA/W-CDMA, but only focused on the reverse link. Herein, in this paper, we consider the same definition of ‘overlay’ in Refs. [7] and [8], and fill the gap.

In this paper, the behavior and overall perfor-

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mance of the TDMA/W-CDMA spectrum overlaid system are completely investigated. For this goal, the co-existence of TDMA and W-CDMA spectrum overlaid system with cellular architecture is discussed. In this system, both systems share the same frequency band to improve the spectrum efficiency. Overall rate, bit error ratio (BER) and spectrum efficiency of the system are calculated for the forward link (down-link). Taking into account the path loss and shadow loss in this system with cellular architecture, W-CDMA applying interference cancellation shows a substantial difference in spectrum efficiency. The overlaid system can provide a greater overall rate and higher spectrum efficiency than a single multiple access-based system such as TDMA system or W-CDMA system. The numerical results show that the interference cancellation (IC) can significantly improve BER of the spectrum overlaid system.

This paper is organized as follows. In Sect. 2, a TDMA/W-CDMA spectrum overlaid system model is proposed. IC principles and all the interference analysis are also described in this section. In Sect. 3, we evaluated the BER performance and spectrum efficiency of the system with and without interference cancellation. Section 4 describes the numerical results and discuss the effects of notch filter and signal clipper on the forward link. We discuss the feasibility of the TDMA/W-CDMA overlaid system and conclude the paper in Sect. 5, finally.

## 2. Overlaid System Models and Interference Analysis

### 2.1 Overlaid System Model

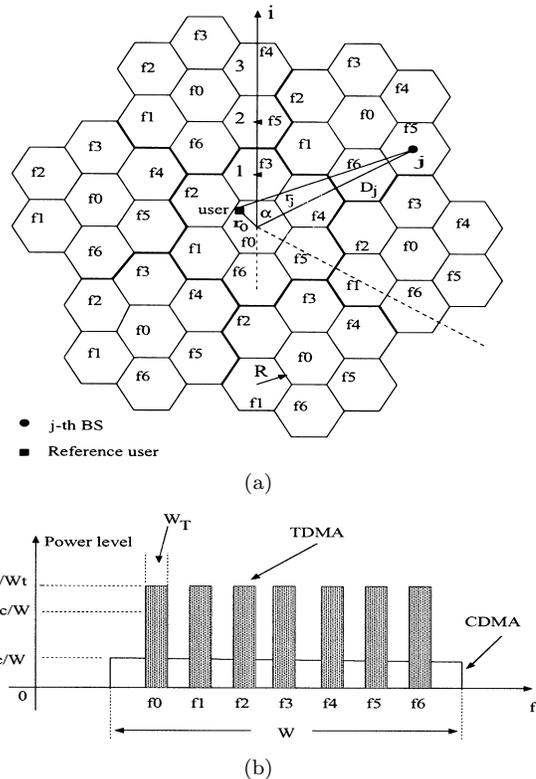
Figure 1 shows a traditional cellular system, where each cell consists of TDMA users and W-CDMA users in TDMA/W-CDMA overlaid system. For the TDMA system, we assign the same channels to each cell with the cluster size,  $K$ , where  $K$  cells form a cluster and share the entire spectral bandwidth. For the W-CDMA system, we assign the entire bandwidth to each cell, using the pseudo-noise (PN) codes, which are uncorrelated, and absolutely to separate the desired signal.

Let us consider a user as the reference user located in the reference cell (0-th cell in Fig. 1(a)) at a distance of  $r_0$  from the reference base station (BS) and at a distance of

$$r_j = \sqrt{r_0^2 + D_j^2 - 2D_j r_0 \cos \alpha} \quad (1)$$

from the  $j$ -th neighboring BS at shown in Fig. 1(a). Where  $r_j$  is the distance from the user to the  $j$ -th surrounding BS.  $D_j$  is the distance between the reference BS and the  $j$ -th surrounding BS, and  $\alpha$  is defined as in Fig. 1(a).

For a radio channel the loss is considered to be



**Fig. 1** Cellular geometry of TDMA/W-CDMA overlaid system in (a) Forward link layout of cellular, (b) Spectrum overlaid structure ( $K = 7$ ).

proportional to the path loss with the law,  $\gamma$  and the other shadow fading effects are also considered as well, the most significant being shadowing presented by a Gaussian random variable  $\lambda$ , which has a zero mean and a standard deviation of  $\sigma$ .  $\sigma$  is the standard deviation of  $\lambda$ . It ranges generally from 5 to 9 dB. Fast fading (due largely to multi-path) is assumed not to affect the average power level because the fast fluctuations can be filtered out by means of proper techniques, such as Rake receiver, diversity and coding with interleave. Here, the impact of path loss and the shadowing loss on the received signal at the receiver can be depicted as [8], [9]

$$S = Pr^{-\gamma} 10^{\lambda/10} \quad (2)$$

where  $S$  is the received signal power at the receiver and  $P$  is the transmitted signal power at the transmitter.  $r$  is the distance between the receiver and transmitter. We assume that there are  $N$  channels and one pilot channel in each cell on the forward link, and the same power,  $P$  is allocated to each channel. Therefore, we investigated the worst case [9] that when the reference user is located at the boundary between cells.

We also set standard limits for the required bit energy-to-noise density ratio,  $(E_b/N_0)_{req}$  as 5 dB for W-CDMA [1], [9] and the required signal-to-interference ratio,  $CIR_{req}^t$  as 12 dB for the TDMA [1]. The TDMA system capacity with the full load, can supporting the

maximum of  $N_t$  users per cell, is expressed as

$$N_t = \frac{n_t W_T}{W_t} \quad (3)$$

where  $n_t$  is the number of TDMA time slot per carrier.  $W_T$  is the total bandwidth of TDMA allocated to one cell, and  $W_t$  is the bandwidth of a TDMA channel.

## 2.2 Interference Cancellation and Interference Analysis

### 2.2.1 Interference Cancellation

As shown in Fig. 1(b) for the bandwidth allocation, where the ordinate is the power level density and the abscissa is the frequency axis. The idea behind the spread spectrum is to transform a signal with narrow-bandwidth into a noise-like signal of much wide-bandwidth  $W$  in W-CDMA system. One of the most attractive characteristics of adopting spread spectrum in wireless cellular system is the ability to overlay wide-band CDMA system, on top of existing narrow-band CDMA or TDMA systems.

Due to the low-power spectrum density, W-CDMA signals cause relatively little interference to TDMA system. On the other hand, TDMA system cause high interference to the W-CDMA system if without any interference suppressions, which limits the overlaid system as a practical way for system evolution. Then, in order to suppress the multi-interference, the notch filter is introduced in the W-CDMA. The notch filter is the limited spectrum filter used in W-CDMA receiver for filtering the part of the overlaid bandwidth of TDMA with the higher power level density. As shown in Fig. 1(b), only  $W_T$  is filtering out in one cell. Notch filter is also used in W-CDMA transmitter for filtering some portion of the overlaid bandwidth in order to reduce some multi-cross interference from the W-CDMA system to the TDMA. Based on Ref. [8], in the overlaid system, the performance could not improved significantly only dependent on the notch filter, so the signal level clipper is adopted. The signal level clipper is a kind of signal level limiter used for suppressing the higher signal level of interference. For ease of understanding, here we define the clipper scope,  $\delta$  as the permitted range of signal level that can pass through the receive channel filter in the receiver that means  $\delta$  times  $S_c/W$  of W-CDMA to be remained as interference generated from TDMA to W-CDMA. So the rejected interference  $I_{rejected}$  from TDMA to W-CDMA is

$$I_{rejected} = W_t \left( \frac{S_t}{W_t} - \delta \frac{S_c}{W} \right) \quad (4)$$

where  $S_t$  and  $S_c$  are the desired signals of TDMA and W-CDMA in one channel, respectively. When  $\delta = 1$ , it means the best case that the maximum interference is rejected. The ideal case is when  $\delta = 0$ , but impossible [6]–[8].

### 2.2.2 TDMA Forward Link

1) *Desired Signal,  $S_t$* : Because the same required transmitted power  $P_t$  is allocated to each channel, the desired signal  $S_t$  is the received signal power when the user dwells at the boundary between cells, which  $S_t$  is equal to  $P_t \cdot R^{-\gamma} 10^{\lambda_0/10}$ .

2) *Intracell and Intercell TDMA Interference to Desired Signal Ratios,  $E[I_{tt}^{in}/S_t, I_{tt}^{out}/S_t]$* : The required signal-to-interference ratio of TDMA channel is assumed to be  $CIR_{req}^t = 12$  dB [1]. This sets an upper-bound of  $CIR$ . We can obtain  $E[(I_{tt}^{in} + I_{tt}^{out} + N_0)/S_t] = 0.0631$ .

3) *Intracell CDMA Interference to Desired Signal Ratio,  $E[I_{ct}^{in}/S_t]$* : Because there are some overlapped portions of bandwidths between the TDMA and W-CDMA bandwidth as shown in Fig. 1(b), and the W-CDMA BS employs perfect notch filter to reject this interference. Then the intracell CDMA interference to the desired signal ratio when the TDMA user dwells at the boundary, is equal to zero.

4) *Intercell CDMA Interference to Desired Signal Ratio,  $E[I_{ct}^{out}/S_t]$* : This interference  $I_{ct}^{out}$ , of W-CDMA system to TDMA system originates from all cells where TDMA occupies the same bandwidth. Below, an average value for this interference is estimated, where we assume a circular cell rather than a true hexagonal cell for simplicity. Notice that  $R$  of the circular cell is essentially the same as  $R$  of a hexagonal cell. The intercell CDMA interference to the desired signal ratio is obtained by the integration of each cell as follows [9], [10]

$$E \left[ \frac{I_{ct}^{out}}{S_t} \right] = \frac{W_t P_c}{W P_t} \sum_{i=1}^m \mu \iint \left( \frac{r_0}{r_j} \right)^\gamma \cdot E \left[ \phi \left( \xi, \frac{r_0}{r_j} \right) 10^{\xi/10} \right] \rho_c dA \quad (5)$$

where  $\mu$  is the voice activity factor [10], [11].  $\xi = \lambda_j - \lambda_0$  and

$$E \left[ \phi \left( \xi, \frac{r_0}{r_j} \right) 10^{\xi/10} \right] = \exp \left( \frac{\sigma \ln(10)}{10} \right)^2 \cdot \left\{ 1 - Q \left[ \frac{10\sigma \log(r_j/r_0)}{\sqrt{2}\sigma} - \frac{\sqrt{2} \ln(10)\sigma}{10} \right] \right\} \quad (6)$$

where  $m$  is the total number of CDMA cells considered in our cellular model,  $\rho_c$  is the user's distribution density function given by  $\rho_c = \frac{N}{2\pi R^2}$  when  $N$  active users are uniformly distributed in the entire area of a cell, and  $E[\phi(\xi, \frac{r_0}{r_j}) 10^{\xi/10}]$  means the expected value of  $10^{\xi/10}$  which could be formulated in Eq. (5) by the attachment Appendix. Here, we defined the ratio of required transmitted power of W-CDMA to that of TDMA as the power ratio,  $\kappa$ . Then it equal to  $P_c/P_t$ .

### 2.2.3 W-CDMA Forward Link

1) *Desired Signal,  $S_c$* : In the W-CDMA user dwelled at the boundary between cells, as the same required transmitted power  $P_c$  for each CDMA channel is transmitted to the each user, the received signal power  $S_c$  will be  $P_c \cdot R^{-\gamma} 10^{\lambda_0/10}$ .

2) *Intracell CDMA Interference to Desired Signal Ratio,  $E[I_{cc}^{in}/S_c]$* : Because there are  $N$  active users controlled by W-CDMA BS in each cell, then  $E[I_{cc}^{in}/S_c] = \mu(N-1)$  [9], [10].

3) *Intercell CDMA Interference to Desired Signal Ratio,  $E[I_{cc}^{out}/S_c]$* : The estimation of the intercell W-CDMA interference is similar to that of  $I_{ct}^{out}$  as follows [9]

$$E \left[ \frac{I_{cc}^{out}}{S_c} \right] = \sum_{i=1}^m \mu \iint \left( \frac{r_0}{r_j} \right)^\gamma \cdot E \left[ \phi \left( \xi, \frac{r_0}{r_j} \right) 10^{\xi/10} \right] \rho_c dA \quad (7)$$

4) *Intracell TDMA Interference to Desired Signal Ratio,  $E[I_{tc}^{in}/S_c]$* : Because of the adoption of perfect notch filter in the CDMA receivers, the W-CDMA users will not experience any interference from the TDMA users in the reference cell, that means  $E[I_{tc}^{in}/S_c] = 0$ .

5) *Intercell TDMA Interference to Desired Signal Ratio,  $E[I_{tc}^{out}/S_c]$* : As shown in Fig. 1, the interference from all the TDMA cells except those reusing the same bandwidth to the W-CDMA should be calculated. Because the bandwidth allocated to the TDMA system is not the same spread spectrum allocated to the W-CDMA system as shown in Fig. 1(b) and  $W$  covers all the TDMA allocated bandwidth, we have to calculate the interference generated from all the surrounding TDMA cells to the W-CDMA. Using the similar method depicted in Sect. 2.2.2(4), we can obtain  $E[I_{tc}^{out}/S_c]$  under considering  $n$  TDMA cells as follows

$$E \left[ \frac{I_{tc}^{out}}{S_c} \right] = \frac{\delta}{W\kappa} \sum_{i=1}^n \iint \left( \frac{r_0}{r_j} \right)^\gamma \cdot E \left[ \phi \left( \xi, \frac{r_0}{r_j} \right) 10^{\xi/10} \right] \rho_t dA \quad (8)$$

where,  $\rho_t = \frac{N_t}{2\pi R^2}$ .

## 3. Performance Evaluation

The average bit error rates (BER) should be obtained by averaging the bit error rates with the probability density function (*pdf*) of  $E_b/N_0$ . There are many papers that investigated the average BER in fading channels, such as Nakagami fading channel [15] and Rayleigh fading channel [16], [17]. It is difficult to obtained the

*pdf* in Ref. [17]. Reference [17] presents an approach to investigate CDMA cellular system and the authors used Laplace transform to get the *pdf*. In our paper, considering TDMA/W-CDMA overlaid system and the effects of shadow with Gaussian distribution, the situation becomes more difficult to derive the *pdf*. Then we used the same methods adopted in Refs. [9] and [13]. In this method, the effects of fading are negligible, the interference generated from other users is estimated as an average value with the effects of shadow. In this case, only the BER, not the average BER has been investigated.

### 3.1 BER Performance of TDMA Signal with W-CDMA Interference

In this TDMA/W-CDMA overlaid system, because CDMA has a lower power level density compared with that of TDMA, so it generates little distortion to TDMA signal. For TDMA system, in AWGN channel the BER without W-CDMA interference is given by  $P_e = \frac{1}{2} \text{erfc}(\sqrt{E_b/N_0})$  (QPSK modulation) [13], [14], in which  $E_b/N_0$  is the bit energy to thermal noise ratio. When TDMA/W-CDMA overlaid system is considered, the BER of TDMA signal is determined by the sum of the thermal noise and the interference generated by the other systems. Then it can be modified as

$$P_e = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{E_b^t}{N_0 + \frac{E_b^t R_b^t}{W} \left( E \left[ \frac{I_{ct}^{in}}{S_t} \right] + E \left[ \frac{I_{ct}^{out}}{S_t} \right] \right)}} \right) \quad (9)$$

where  $E_b^t$  and  $R_b^t$  are the one bit energy and information rate of TDMA system, respectively. When the power of TDMA signal is large enough that means  $\kappa \ll 1$ , the effects of W-CDMA on TDMA could be ignored in the investigation shown in Fig. 5.

### 3.2 BER Performance of W-CDMA with and without Notch Filter

The power of TDMA interference to W-CDMA system has been calculated in above sections. Because the received signals composed of W-CDMA signal and TDMA signal are multiplied by a Gold code for despreading at the W-CDMA receiver, the narrow-band interference generated by TDMA is also spread out and its power density is decreased.

In this paper, The W-CDMA signal is also based on QPSK modulation/coherent demodulation format with Gold codes. The power of the interference in the system was evaluated in the above section. Since the received signal is multiplied by the orthogonal Gold codes for spreading at the W-CDMA receiver, the narrow-band interference is spread out and its power spectrum density is also reduced, therefore the total average interference power is determined only by the total interference to the processing gain ratio. In an AWGN

channel, the BER of W-CDMA system with a single cell, which is originally derived in Refs. [12] and [13] as

$$P_{BER} = \frac{1}{2} \text{erfc} \left\{ \sqrt{\frac{E_b^c}{N_0 + \frac{2}{3} E_b^c \frac{N-1}{G_p}}} \right\}, \quad (10)$$

where  $G_p$  is the processing gain [1],[2]. In the TDMA/W-CDMA overlaid system with cellular architecture, the BER of CDMA signal is determined by the sum of the thermal noise, intracell interference and intercell interference from the surrounding cells, and the interference from other systems. In our case, the above formula can be modified as

$$P_{BER} = \frac{1}{2} \text{erfc} \left\{ \sqrt{\frac{E_b^c}{N_0 + \frac{2}{3} E_b^c \frac{N-1}{G_p} + \frac{E_b^c R_b^c}{W} \left( E \left[ \frac{I_{cc}^{out}}{S_c} + \frac{I_{tc}}{S_c} \right] \right)}} \right\} \quad (11)$$

here,  $E_b^c$  and  $R_b^c$  are the one bit energy and information rate of W-CDMA system, respectively.  $I_{cc}^{out}$  is the interference generated by the surrounding W-CDMA cells. In our case, there is interference generated from the TDMA.  $I_{tc}$  is the total interference generated by TDMA to W-CDMA which can be expressed as  $I_{tc} = I_{tc}^{in} + I_{tc}^{out}$ . In our case,  $I_{tc}^{in} = 0$  because of the adoption of notch filter.

### 3.3 Spectrum Efficiency

In order to consider the feasibility of the overlaid systems, it is necessary to calculate the spectrum efficiency when the systems adopt either the overlaid spectrum-shared or spectrum-partitioned. To delineate it, we simply define the spectrum efficiency as the overall rate (total bit rate) carried in one cell for one MHz. A convenient measure of the spectrum efficiency of the overlaid system is in terms of kbps/MHz/cell [14]. The overall rate of the overlaid system is given by the sum of the bit rates of all systems as  $A_c + A_t$  for the TDMA/W-CDMA overlaid system, where  $A_c$ , and  $A_t$  are the overall rates of the W-CDMA and TDMA systems, respectively.

Therefore in this section, we investigated the forward link spectrum efficiency among a W-CDMA system, a TDMA system and a TDMA/W-CDMA overlaid system with notch filter and signal clipper. In the spectrum overlaid system, the bandwidth occupied by the systems is the spread bandwidth assigned to the W-CDMA,  $W$  in MHz. In the bandwidth-partitioned, the bandwidth occupied by the systems is the sum of the bandwidths assigned to each system.

#### 1) Spectrum Efficiency of the W-CDMA and TDMA Systems

For a forward link channel of W-CDMA system with multiple access scheme, the total received power

at the reference user dwelled at the boundary is given as

$$P_{total} = N_c R_b^c E_b^c \quad (12)$$

where  $N_c$  is the system capacity of W-CDMA system, that is defined as the maximum number of active users in each cell when the inequality,  $CIR \geq \frac{(E_b/N_0)_{req}}{G_p}$  has been satisfied. If we only consider W-CDMA cellular system, the total interference to desired signal ratio  $ISR$  ( $ISR = 1/CIR \leq \frac{G_p}{(E_b/N_0)_{req}}$ ) can be obtained as the linear function of  $N$  as

$$\begin{aligned} ISR &= E[I_{cc}^{in}/S_c] + E[I_{cc}^{out}/S_c] \\ &= \mu(N-1) + \sum_{i=1}^m \mu \iint \left( \frac{r_0}{r_j} \right)^\gamma \\ &\quad \cdot E \left[ \phi \left( \xi, \frac{r_0}{r_j} \right) 10^{\xi/10} \right] \frac{N}{2\pi R^2} dA \\ &\leq \frac{G_p}{(E_b/N_0)_{req}} \end{aligned} \quad (13)$$

After simplistic derivation, the inequality equation can be transformed to

$$N \leq \frac{\frac{G_p}{(E_b/N_0)_{req}} - \mu}{\mu \left( 1 - \sum_{i=1}^m \iint \left( \frac{r_0}{r_j} \right)^\gamma E \left[ \phi \left( \xi, \frac{r_0}{r_j} \right) 10^{\xi/10} \right] \frac{1}{2\pi R^2} dA \right)} \quad (14)$$

Then the maximum number of active users in each cell referred to system capacity as  $N_c$  that can be obtained as the maximum value of  $N$ . When the TDMA/W-CDMA overlaid system is investigated, the TDMA interference to desired signal ratio,  $E[I_{tc}^{in}/S_c]$  and  $E[I_{tc}^{out}/S_c]$  must be added in the calculation to determine the CDMA system capacity.

If  $P_{total}$  is divided by  $(N_0 + I_{total})W$ , we get

$$\frac{P_{total}}{(N_0 + I_{total})W} = \frac{N_c R_b^c}{W} \frac{E_b^c}{N_0 + I_{total}} \quad (15)$$

Then the spectrum efficiency can be obtained as  $\eta_c$  as follows

$$\eta_c = \frac{N_c R_b^c}{W} = \frac{\frac{P_{total}}{N_0 W}}{\frac{E_b^c}{N_0}} \quad (16)$$

Because each user adopts the same spread bandwidth, the total interference is the sum of thermal noise, the spectral density of internal interference from  $N_c - 1$  users in itself cell and the outside interference from the other cells, then the total interference,  $N_0 + I_{total}$  can be described as

$$N_0 + I_{total} = N_0 + \frac{E_b^c R_b^c}{W} \left( N_c - 1 + E \left[ \frac{I_{cc}^{out}}{S_c} \right] \right) \quad (17)$$

Then

$$\frac{E_b^c}{N_0} = \frac{E_b^c}{N_0 + I_{total}} \left( 1 + \frac{P_{total}}{N_c W N_0} \left( N_c - 1 + E \left[ \frac{I_{cc}^{out}}{S_c} \right] \right) \right) \quad (18)$$

If we substitute the Eq. (17) into Eq. (15), we can get the spectrum efficiency of the W-CDMA system.

For a forward link channel of TDMA system with the cluster size  $K$ , the total received power at the reference user dwelled at the boundary is given as

$$P_{total} = N_t R_b^t E_b^t = \frac{n_t W R_b^t E_b^t}{K W_t} \quad (19)$$

Then the spectrum efficiency can be defined as  $\eta_t$  as follows

$$\eta_t = \frac{n_t R_b^t}{K W_t} \quad (20)$$

## 2) Spectrum Efficiency of the TDMA/W-CDMA Overlaid System

When we consider the TDMA/W-CDMA overlaid system, the spectrum efficiency,  $\eta_{t/c}$  is given by the following equation according to its definition as

$$\eta_{t/c} = \frac{A_c + A_t}{W} = \frac{N_c R_b^c}{W} + \frac{N_t R_b^t}{W} \quad (21)$$

where,  $N_c$  and  $N_t$  are the capacities of the W-CDMA and the TDMA systems when the two systems are sharing the same bandwidth. In order to calculate  $N_c$  and  $N_t$  that are the total interference limited, the total interference for the W-CDMA system is calculated by the sum of the thermal noise, the mutual interference in W-CDMA itself and the interference generated from the TDMA system with the frequency sharing portion. On the other hand, the total interference for the TDMA system is the sum of the thermal noise, and the interference from the CDMA system. Like Eqs. (16) and (20),  $\eta_{c/t}$  can be derived as

$$\begin{aligned} \eta_{c/t} &= \frac{\frac{P_{total}}{N_0 W}}{\frac{E_b^c}{N_0 + I_{total}} \left( 1 + \frac{P_{total}}{N_c W N_0} \left( N_c - 1 + E \left[ \frac{I_{cc}^{out}}{S_c} \right] + E \left[ \frac{I_{tc}^{out}}{S_c} \right] \right) \right) + \frac{n_t R_b^t}{K W_t}} \end{aligned} \quad (22)$$

According to the analysis in Sect. 2.2, we can complete the calculation of Eqs. (16), (20) and (22) and obtain the numerical results expressed in the following section.

## 4. Numerical Results

In order to derive some numerical results, we summarized the system parameters and specifications as follows:

1) Propagation model and cellular structure parameters:

- Path loss exponent  $\gamma = 4.0$ ;
- Standard variance  $\sigma = 6, 7, 8, 9$  dB;
- Cell radius  $R = 10$  km;

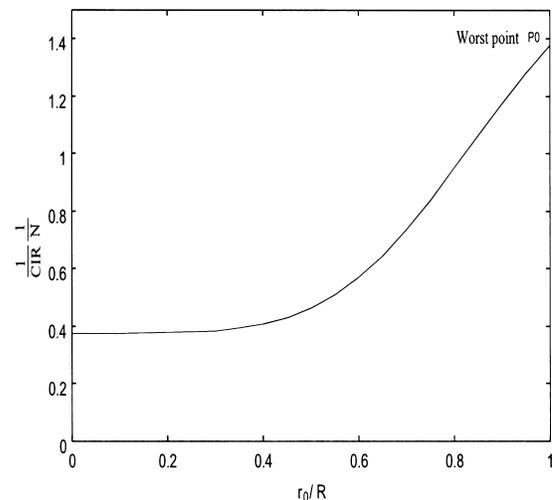
2) System parameters and specifications of W-CDMA:

- QPSK modulation [13], [14];
- Allocated bandwidth of W-CDMA  $W = 25$  MHz;
- Information rate  $R_b^c = 9.6$  kbps;
- Voice activity factor  $\mu = 0.375$ ;
- Power ratio  $\kappa = 1, 0.1$  and  $0.01$ ;
- Permitted range  $1 \leq \delta \leq 20$ ;
- $(E_b/N_0)_{req} = 5$  dB;

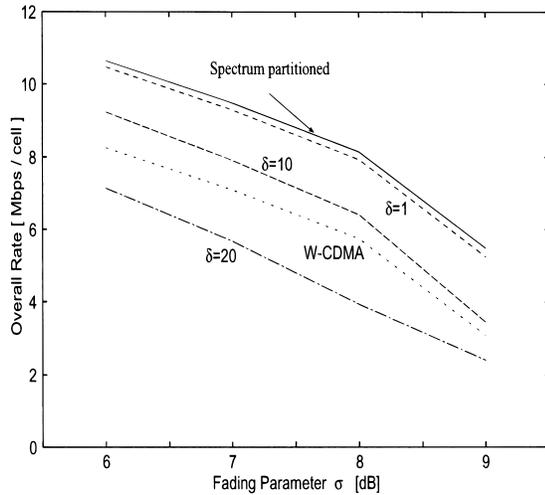
3) System parameters and specifications of TDMA:

- QPSK modulation [13], [14];
- Allocated bandwidth of TDMA  $W_T = 1.25$  MHz;
- Information rate  $R_b^t = 9.6$  kbps;
- Bandwidth of one channel in TDMA  $W_t = 30$  kHz (U.S. standard);
- Cluster size of TDMA  $K = 7$ ;
- Full rate channels in TDMA  $n_t = 6$  (U.S. standard);
- $CIR_{req}^t = 12$  dB

For a CDMA system, the total interference to signal ratio,  $1/CIR$  in terms of the active number of users,  $N$  per cell for different values of normalized distance  $r_0/R$  can be calculated from Sect. 2.2.3(2) and Eq. (7). By considering the many surrounding interfering cells shown in Fig. 1(a), the curve of the forward link  $1/CIR$  when  $r_0/R$  is from zero to one, that means the user dwells from near its *BS* to the boundary between cells, is shown in Fig. 2 for  $\mu = 0.375$  and  $\sigma = 8$  dB. According to the curve variation, the transmission quality for users near its *BS* is better than that for users dwelled at the boundary. In order for a *BS* to serve all the users in its cell with a minimal transmission quality requirement, the system capacity tends to be limited by the users at the boundary. The worst point is when users



**Fig. 2**  $\frac{1}{CIR} \frac{1}{N}$  of forward link versus the normalized distance  $r_0/R$  without the power control scheme ( $\sigma = 8$  dB).



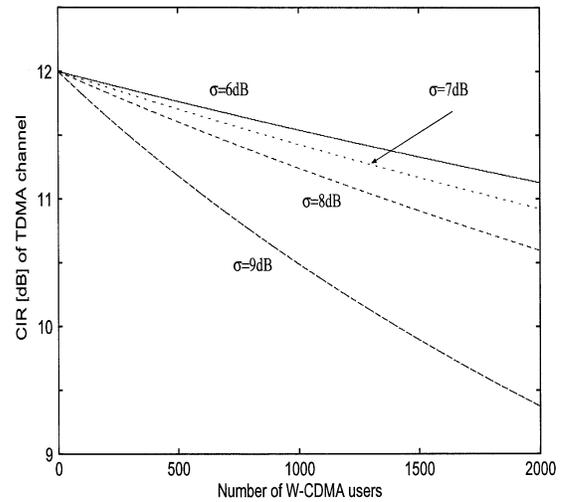
**Fig. 3** Overall rate versus the parameter  $\sigma$  with diverse  $\delta$  ( $\kappa = 0.01$ ).

are dwelling at the boundary among cells shown as  $P_0$  in Fig. 2. For a TDMA, the same situation will be occurred when users are dwelling at the boundary where the interference will be the largest. Then the numerical results given in following are the worst results.

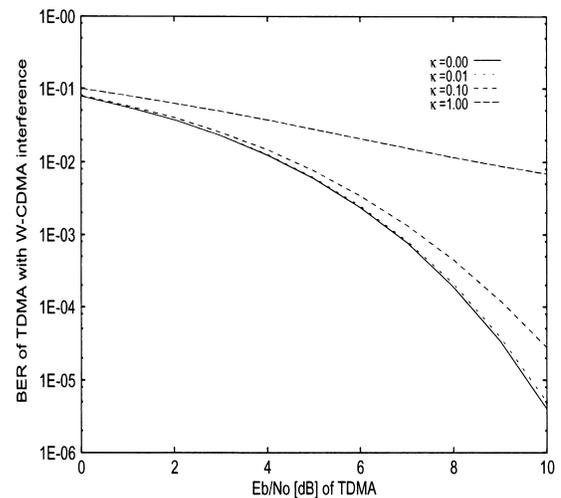
Figure 3 shows the overall rate of W-CDMA system and the overall rate of the TDMA/W-CDMA overlaid system with different clipper scope,  $\delta$  for  $\sigma$ . From this figure, we know when  $\sigma$  increases, the overall rate monotonically decreases. The overall rate of the system is very sensitive to  $\delta$ . If  $\delta$  is less than 10, the overall rate of TDMA/W-CDMA overlaid system is larger than that of W-CDMA, otherwise, it is worse. According to the features of forward link, that is not enough only dependent on notch filter to reject interference for improving the system performance, we must adopt signal clipper and set  $\delta \leq 10$  in order to ensure higher overall rate and higher spectrum efficiency.

The most important parameter,  $CIR$  of TDMA channel due to the overlay for various values of  $\sigma$  is depicted in Fig. 4 where one can see the effects of the W-CDMA on the TDMA with spectrum overlaid. For different situations of  $\sigma$  the decrease of  $CIR$  is not so critical when the wireless mediums are under slight and intermediate shadowing in the forward link.

In the spectrum overlaid system, the BER of TDMA channel is calculated by Eq. (9) and drawn in Fig. 5 with the effects of W-CDMA for different power ratio  $\kappa$  between the two systems. From the figure, the curve with a solid line shows the BER of TDMA channel that agrees well with the results of Ref. [13] without the effects of W-CDMA with full load. When the W-CDMA system is introduced and sharing some portion of spectrum, its effects on the BER of TDMA channel are shown in other curves.  $\kappa$  is the power ratio defined as  $P_c/P_t$ . It affects the multi-cross interference between W-CDMA and TDMA, so it could not be too larger or



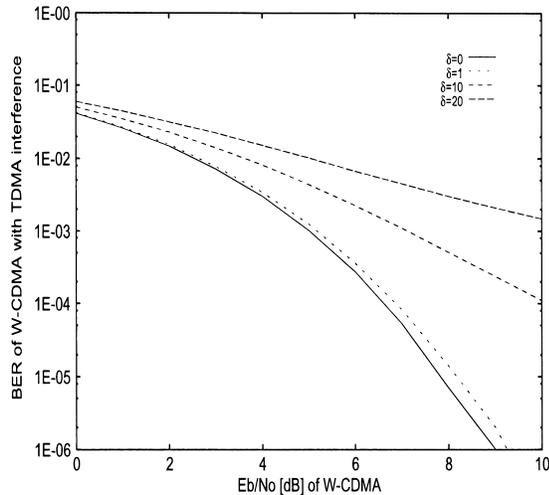
**Fig. 4** CIR [dB] of TDMA channel versus the number of W-CDMA users under various  $\sigma$  ( $\kappa = 0.01$ ).



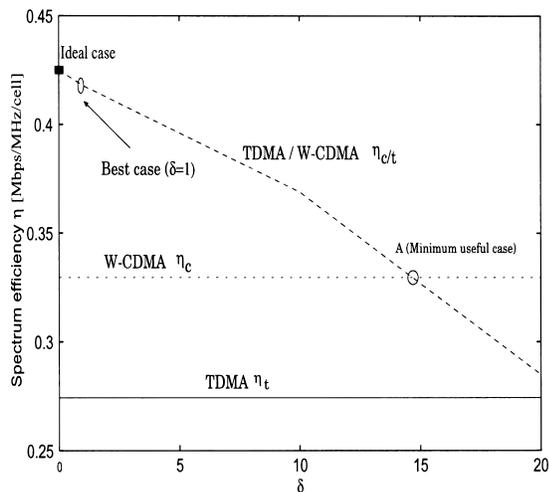
**Fig. 5** BER of TDMA channel versus  $E_b/N_0$  with various power ratio  $\kappa$  under the full load of W-CDMA,  $N_c$ .

too smaller. The larger it is, the bigger interference is generated from W-CDMA to TDMA that degrades the BER of TDMA channel shown in Fig. 5. On the other hand, the smaller it is, the larger interference is generated from TDMA to W-CDMA that will also degrade BER of W-CDMA channel. According to Fig. 5, if we define an acceptable BER tolerance in the range of  $[1.0E-03, 5.0E-03]$  in which  $BER=1.0E-03$  is the required criterion for speech services [13], the values of  $\kappa$  should be chosen from 0.1 to 0.01. From the figure, one can see that the case could not be accepted when  $\kappa = 1.00$ .

On the other hand, the BER of W-CDMA must be investigated for the spectrum overlaid system that is shown in Fig. 6 where the diverse clipper permitted range,  $\delta$  is considered. During the investigation, the TDMA/W-CDMA overlaid system with power ra-



**Fig. 6** BER of W-CDMA channel versus  $E_b/N_0$  with diverse  $\delta$  under the full load of TDMA,  $N_t$  ( $N_t = 250$  users/cell,  $\kappa = 0.01$ ).



**Fig. 7** Spectrum efficiency  $\eta$  of the TDMA/W-CDMA overlaid system versus  $\delta$  when  $\sigma = 6$  dB ( $N_t = 250$  users/cell,  $\kappa = 0.01$ ).

tion  $\kappa = 0.01$  and full load of TDMA is considered. The curve of a solid line shows the BER of W-CDMA channel without the effects of TDMA that is very agreeable with the conventional results used in many researches that  $\text{BER} = 1\text{E-}03$  threshold when  $E_b/N_0 = 5$  dB for forward link [1], [9].  $\delta$  is the permitted range that determines how much interference generated from TDMA, will be remained in affecting the W-CDMA system performance. If we set  $\delta$  larger, the larger interference will be remained. The values of  $\delta$  should be chosen from 1 to 10 if we also define the BER tolerance in the range of  $[1.0\text{E-}03, 5.0\text{E-}03]$  as shown in Fig. 6. From Fig. 7, one also see that  $\eta_{c/t}$  will be increased over 10 percents than  $\eta_c$  when  $\delta$  is from 1 to 10.

Figure 7 shows the spectrum efficiency of the TDMA/W-CDMA overlaid system with the notch filter and signal clipper by various clipper scope,  $\delta$ . We

calculated the spectrum efficiency of TDMA system, W-CDMA system and the proposed TDMA/W-CDMA overlaid system, respectively when  $\sigma = 6$  dB. From this figure, we see the spectrum efficiency of W-CDMA is larger than that of TDMA. When the two systems are sharing the same spectrum, theoretically the best ideal case ( $\eta_c + \eta_t$ ) is occurred as shown in this figure that means the multi-cross interference can be entirely rejected. It is impossible to achieve this case. In practice, after introducing some interference rejection technologies, we see the spectrum efficiency of TDMA/W-CDMA overlaid system is largest among three systems, especially when  $\delta \leq 15$ . It shows the more users can be supported in the TDMA/W-CDMA overlaid system that also means the system capacity is increased. For the numerical results, the spectrum efficiency will be 27.3 percents higher than that of W-CDMA when  $\delta = 1$  (Best case in practice) and nearly equal to that of when  $\delta = 15$  (referred to the minimum useful case in Fig. 7). When  $\delta \geq 15$ , it will be less than that of W-CDMA system, but higher than that of TDMA system.

## 5. Conclusions

In this paper, we study an important question for operators that is whether the TDMA/W-CDMA overlaid system can reuse the same bandwidth or not. Below what conditions, the system can be adopted as commercial applications and the effects between TDMA system and W-CDMA system are shown in relative subsections. In particular, BER performance and spectrum efficiency of forward link are investigated. According to the numerical results, the analysis shows the followings.

Without notch filter and signal clipper, any overlaid systems by employing bandwidth overlaid can not be achieved in practical situation because of significant multi-cross interference problems between TDMA system and W-CDMA system.

In order to make the overlaid system as practical applications, it is very necessary to use the notch filter for rejecting only part of intracell interference generated from TDMA system, but intercell interference generated from TDMA system could not be rejected. So in order to decrease this interference, the signal clipper is introduced with the clipper scope,  $\delta$ , especially,  $\delta$  must be less than 15, the higher the spectrum efficiency is gotten for the system.

In our system example, the TDMA/W-CDMA overlaid system can provide a greater system capacity than that of a single multiple access-based system, such as TDMA system or W-CDMA system. The spectrum efficiency will be improved 27.3 percents higher than that of W-CDMA system in the best case shown in Fig. 7.

Here, we dealt with the issue about the feasibility of the TDMA/W-CDMA overlaid system, but the

power control issues have not considered. The analytical method depicted in this paper could be easily extended to treat the reverse link and additional performance works such as outage probability and throughput when power control schemes are adopted that are our future works.

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### Appendix: Evaluation of $E[\phi(\xi, \frac{r_0}{r_j})10^{\xi/10}]$

In order to estimate  $E[\phi(\xi, \frac{r_0}{r_j})10^{\xi/10}]$ , according to the radio channel model depicted in Eq. (2), we consider the user of TDMA or W-CDMA as the reference user in the forward link. The users in the other cells are controlled by other base stations. Consequently, if the interfering user is in another cell, its signal power is transmitted from this cell base station. This signal power reaches the reference user at a distance  $r_j$ , that is considered as the intercell interference. Then the interference to desired signal ratio is equal to

$$\frac{I(r_0, r_j)}{S} = \left(\frac{r_0}{r_j}\right)^\gamma 10^{(\lambda_j - \lambda_0)/10} \quad (\text{A} \cdot 1)$$

The mean of  $\frac{I(r_0, r_j)}{S}$  is

$$E\left[\frac{I(r_0, r_j)}{S}\right] = \left(\frac{r_0}{r_j}\right)^\gamma E\left[\phi\left(\xi, \frac{r_0}{r_j}\right)10^{\xi/10}\right] \quad (\text{A} \cdot 2)$$

where in Eq. (A.2),  $\xi = \lambda_j - \lambda_0$  is a Gaussian random variable which has zero mean and standard deviation of  $\sigma_\xi^2$  ( $\sigma_\xi^2 = 2\sigma^2$ ) as  $\lambda_0$  and  $\lambda_j$  are independent random variables.  $\phi(\xi, \frac{r_0}{r_j})$  is the unit function which is equal to one when  $\frac{I(r_0, r_j)}{S} \leq 1$  ( $\xi \leq 40 \log(r_0/r_j)$ ), otherwise it equal to zero. That means the user located at the boundary among cells tending to communicate to a BS that offers the least signal attenuation, otherwise soft-handoff occur [1]. Based on the previous principle,  $E[\phi(\xi, \frac{r_0}{r_j})10^{\xi/10}]$  in the denominator of Eq. (A.2) can be obtained as

$$\begin{aligned} & E\left[\phi\left(\xi, \frac{r_0}{r_j}\right)10^{\xi/10}\right] \\ &= \int_{-\infty}^{40 \log(r_0/r_j)} \exp(\xi \ln 10/10) \cdot \frac{\exp(-\xi^2/2\sigma_\xi^2)}{\sqrt{2\pi\sigma_\xi^2}} d\xi \\ &= \exp\left(\frac{\sigma \ln(10)}{10}\right)^2 \\ &\cdot \left\{1 - Q\left[\frac{10\sigma \log(r_j/r_0)}{\sqrt{2}\sigma} - \frac{\sqrt{2} \ln(10)\sigma}{10}\right]\right\} \end{aligned} \quad (\text{A} \cdot 3)$$

where,

$$Q(x) = \int_x^{\infty} e^{-\frac{y^2}{2}} dy / \sqrt{2\pi} \quad (\text{A.4})$$



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