Suppressing Opposite-Direction Interference in TDD/CDMA Systems With Asymmetric Traffic by Antenna Beamforming

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***Abstract*—One of the key advantages for the time-division duplex (TDD) system is the capability to deliver asymmetric traffic services by allocating different numbers of uplink and downlink time slots. However, in a TDD/code-division multiple-access (CDMA) system, asymmetric traffic may result in severe *opposite-direction interference* because *downlink* transmitted signals from neighboring base stations may interfere with the *uplink* received signals of the home cell. In this paper, we investigate the effect of four-antenna beamforming schemes from the perspective of suppressing the opposite-direction interference. We compare the uplink bit energy-to-interference density ratio of a traditional beam-steering technique (Scheme I) with that of the minimum-variance distortionless-response (MVDR) beamformer (Scheme II). Furthermore, Scheme III applies the conventional beam-steering technique for both downlink transmissions and the uplink reception. In Scheme IV, we implement beam-steering for downlink transmissions, while adopting the MVDR beamformer to process the uplink signals received at base stations. Our numerical results indicate that Scheme IV outperforms all the other three schemes, which can effectively suppress the strong opposite-direction interference in TDD/CDMA systems. While keeping low implementation costs in mind, employing the simpler Scheme III in a sectorized cellular system can also allow every cell to provide different rates of asymmetric traffic services.**

***Index Terms*—Adaptive arrays, beamforming, code-division multiple-access (CDMA), land mobile cellular systems, time-division switching.**

I. Introduction

In FUTURE wireless Internet services, the traffic volume in the downlink direction is expected to be much higher than that in the uplink direction. The time-division duplex (TDD) system can support asymmetric traffic services in an unpaired frequency band by allocating different numbers of time slots in the uplink and downlink [1]–[3]. However, in the TDD/CDMA system, because uplink and downlink transmissions share the same frequency band in every cell, additional interference can occur when a base station receives uplink signals in the time slots that are also used for downlink transmissions in other cells. Fig. 1 illustrates a typical interference scenario in the TDD/CDMA system. Assume that cells A and B in this figure have different rates of traffic asymmetry and allocate time slots independently according to their own traffic requirements. During a particular time slot t_o, one can find that the uplink received signals at cell A may suffer strong interference from the downlink transmitted signals of the neighboring cell B. In this paper, we call this kind of base station-to-base station interference the *opposite-direction interference*, because the desired signal is in the *uplink* direction, while the interference is from the *downlink* direction.

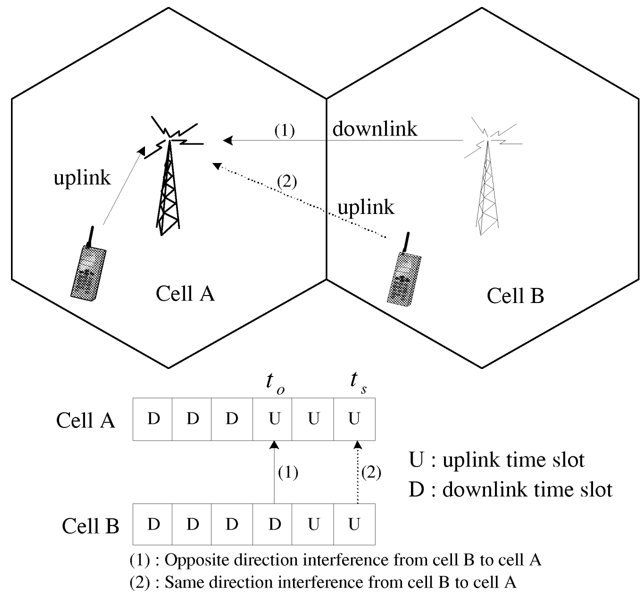

Fig. 1. Opposite-direction interference in the TDD/CDMA system.

On the other hand, in time slot t_s of Fig. 1, the uplink transmissions from the users in cell B will interfere with the uplink signals of cell A. We call this kind of mobile station-to-base station interference the *same-direction interference*. The same-direction interference also occurs in frequency-division-duplex (FDD)/CDMA systems. Many previous works, such as [4] and [5], have analyzed the impact of the same-direction interference. Thanks to power-control mechanisms and other techniques, the impact of the same-direction interference can be effectively managed in FDD/CDMA systems. However, the opposite-direction interference, which is unique in TDD/CDMA systems, is substantially different from the same-direction interference. First, it is difficult to coordinate many base stations throughout the entire service area to perform downlink power control simultaneously. Moreover, since the transmitter power of a base station is much higher than that of a mobile station, the opposite-direction interference introduced

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by the neighboring base stations will severely degrade the quality of uplink signals transmitted from a mobile station [6]–[8].

In this paper, we focus on the uplink performance of TDD/CDMA systems. Traditionally, to avoid the opposite-direction interference in TDD/CDMA systems, we usually use different frequency carriers among adjacent cells. Obviously, this approach sacrifices frequency reuse efficiency. To use the same frequency carriers in every TDD/CDMA cell, one possible solution to avoid the opposite-direction interference is to restrict all the neighboring cells to adopting the same slot-allocation pattern [9], i.e., all the assignments for either uplink or downlink transmissions in every time slot are the same. However, this approach implies that all cells will be forced to adopt the same rate of traffic asymmetry in the entire system, which obviously is not a very practical restriction. The key to relax this restriction is to overcome the opposite-direction interference in the TDD/CDMA system.

In the literature, there are two research directions to avoid the opposite-direction interference. The first research direction is from the perspective of channel-assignment techniques, such as [3] and [8]. In [3], Haas and McLaughlin proposed a dynamic channel-assignment algorithm to reduce the occurrence of the opposite-direction interference due to asymmetric traffic. However, the authors in [8] concluded that it may be difficult to achieve the optimal time-slot allocation in an environment with multiple TDD/CDMA cells. Another research direction to alleviate the impact of the opposite-direction interference in TDD/CDMA systems is to apply advanced antenna techniques [2], [10]–[12]. The authors in [2] and those in [10] proposed to adopt sector antennas combined with time-slot allocation methods to suppress the opposite-direction interference for the TDD/CDMA system and for the TDD/time-division mutliple-access (TDMA) system, respectively. In [11], Choi and Murch suggested to employ a pre-RAKE transmitter to improve the downlink performance of the TDD/CDMA system and apply spatial diversity to improve the uplink performance. In [12], a joint space–time detection technique was presented to improve the uplink performance of the TD-SCDMA system.

Compared with other categories of smart antenna technology, beamforming is known for its capability of suppressing strong interference [20], [21]. In addition, beamforming can easily exploit the reciprocity of TDD channels to leverage the benefit of joint downlink and uplink beamforming. Thus, beamforming is a promising technology in resolving the opposite-direction interference of TDD/CDMA systems. The application of beamforming technique in FDD/CDMA systems has been studied extensively [13]–[15]. To our knowledge, in the context of the TDD/CDMA system with consideration of asymmetric traffic, the performance improvements by adopting antenna beamforming techniques have not been fully studied in the literature yet. The goal of this paper is, from a system perspective of the TDD/CDMA cellular network, to investigate how to effectively apply antenna beamforming techniques to suppress the opposite-direction interference. To this end, we evaluate two types of antenna beamformers: the conventional beam-steering technique and the minimum-variance distortionless-response (MVDR) beamformer. We will derive the received bit energy-to-interference density ratio[1] of TDD/CDMA signals in the presence of opposite-direction interference and evaluate how these two antenna beamforming techniques can improve the performance.

In addition, we exploit the channel reciprocity of TDD systems and propose to incorporate downlink transmitting beamforming at base stations. Although downlink transmitting beamforming can significantly enhance the downlink capacity of a cellular system [15], [16], it is still a challenging task to implement the optimal downlink beamforming solution. Specifically, the optimal downlink beamforming solution requires sophisticated calculations for the beamformer weights of all users and the transmission power levels of all base stations in the entire network [15], [16]. In order to get insight into how to leverage the synergy of combining transmitting and receiving beamforming, we adopt a simpler downlink beam-steering technique in this paper. We believe that the concept of simultaneously using transmitting and receiving beamformers is new in the TDD/CDMA system because the synergy of combining the downlink transmitting and uplink receiving beamforming has not been fully investigated from a system perspective, i.e., from the angle of suppressing the opposite-direction interference.

In summary, the ultimate goal of this paper is to examine if every cell in the TDD/CDMA system is allowed to provide asymmetric traffic services with greater flexibility, but without suffering the opposite-direction interference. It is noteworthy that, in this paper, we assume that the rates of traffic asymmetry of all cells are different from each other. We will investigate the effect of the following four-antenna beamforming schemes:

- Scheme I: uplink receiving beam-steering method is employed at base stations;
- Scheme II: uplink receiving MVDR beamformer is employed at base stations;
- Scheme III: beam-steering method is jointly applied in both the downlink transmission and uplink reception at all base stations;
- Scheme IV: downlink transmitting beam-steering and the uplink receiving MVDR beamformer are jointly employed at all base stations.

The rest of this paper is organized as follows. In Section II, we formulate and analyze the issue of the opposite-direction interference in the TDD/CDMA cellular system. In Section III, we derive the uplink bit energy-to-interference density ratio for Schemes I and II. In Section IV, we extend our analysis to incorporate downlink transmitting beamforming (Schemes III and IV). Section V shows the numerical results of the four aforementioned beamforming schemes. In Section VI, we provide our concluding remarks.

II. System Model

In this paper, we consider a TDD/CDMA cellular system with seven cells, as shown in Fig. 2, where the home cell is

[1]The bit energy-to-interference density ratio could be more accurately expressed as the bit energy-to-interference-plus-noise density ratio. For ease of presentation, we will use the former term throughput the paper.

indexed with $k=0$ and six adjacent cells are labeled from 1 to 6. Assume that cell 0 in the center is in the uplink mode during a particular time slot t_o. Let $\mathcal{B}_{\rm od}$ and $\mathcal{B}_{\rm sd}$ denote the set of the neighboring cells during time slot t_o operating in the downlink mode and those operating in the uplink mode, respectively. Fig. 2 illustrates an example with $\mathcal{B}_{\rm od}=\{2,4,6\}$ and $\mathcal{B}_{\rm sd}=\{1,3,5\}$. In this example, downlink transmissions of cells 2, 4, and 6 will cause the opposite-direction interference (i.e., the base station-to-base station interference) to the uplink receiving signals of cell 0, while cells 1, 3, and 5 result in the same-direction interference (i.e., the mobile stations-to-base station interference).

In our model, we consider propagation loss and log-normal distributed shadowing. Then, the link gain $G(r,\alpha)$ between the transmitter and receiver is described as

$$G(r,\alpha)=\kappa_0 r^{-m}10^{\alpha/10} \tag{1}$$

where r is the propagation distance, κ_0 is a constant, m is the path-loss exponent, and α is a normal distributed random variable with zero mean and standard deviation of σ dB. Let P_T be the total transmit power of a base station and d_k the distance from cell k $(k\in\mathcal{B}_{\rm od})$ to the home cell. Then, the total opposite-direction interference introduced by the adjacent cells is equal to

$$I_{\rm od}=\sum_{k\in\mathcal{B}_{\rm od}} P_T G(d_k,\alpha_k). \tag{2}$$

Assume that uplink power control is ideally executed so that the received signal power of each mobile user is maintained at a constant level P_r at base stations. Then, the same-direction interference introduced by mobile i_k of $\mathcal{B}_{\rm sd}$ $(k\in\mathcal{B}_{\rm sd})$ is equal to

$$\begin{aligned}I_{i_k}&=\frac{P_r G(r_0,\alpha_0)}{G(r_{i_k},\alpha_{i_k})}\\&=P_r\left(\frac{r_{i_k}}{r_0}\right)^m 10^{(\alpha_0-\alpha_{i_k})/10}\end{aligned} \tag{3}$$

where r_0 and r_{i_k} are the distance from mobile i_k of $\mathcal{B}_{\rm sd}$ to cell 0 and that to cell k $(k\in\mathcal{B}_{\rm sd})$, respectively. For ease of notation, let

$$\beta_{i_k}=\left(\frac{r_{i_k}}{r_0}\right)^m 10^{(\alpha_0-\alpha_{i_k})/10}. \tag{4}$$

Note that the term $\alpha_0-\alpha_{i_k}$ in (4) can be represented by another normal distributed random variable with a modified standard deviation [4]. Let N_k denote the number of mobile users in cell k $(k\in\mathcal{B}_{\rm sd})$ that are in their uplink transmission cycles during a particular time slot t_o. Then, from (3) and (4), the total same-direction interference introduced by adjacent cells can be expressed by

$$\begin{aligned}I_{\rm sd}&=\sum_{k\in\mathcal{B}_{\rm sd}}\sum_{i_k=1}^{N_k} I_{i_k}\\&=\sum_{k\in\mathcal{B}_{\rm sd}}\sum_{i_k=1}^{N_k} P_r\beta_{i_k}.\end{aligned} \tag{5}$$

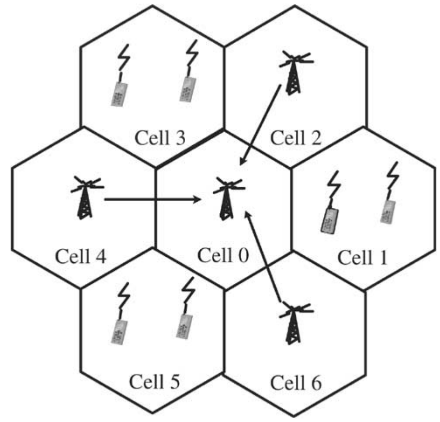


Fig. 2. Example to illustrate the interference scenario in the TDD/CDMA system, where $\mathcal{B}_{\rm od}$ =2, 4, 6 represents the set of the neighboring cells generating the opposite-direction interference and $\mathcal{B}_{\rm sd}$ =1, 3, 5 represents the cells generating the same-direction interference.

In addition to the opposite- and same-direction interfering signals, there still exists the intracell interference in the TDD/CDMA system, denoted as $I_{\rm ic}$. Since power control is assumed to be ideal, the received signal power of all users in a cell will be maintained at a constant level P_r. Thus, $I_{\rm ic}$ can be expressed as

$$I_{\rm ic}=P_r(N_0-1) \tag{6}$$

where N_0 is the number of mobile users in the home cell that are transmitting uplink signals in time slot t_o. Thus, based on the definitions of $I_{\rm od}$, $I_{\rm sd}$, and $I_{\rm ic}$ corresponding to (2), (5), and (6), respectively, the uplink received bit energy-to-interference density ratio γ_i for a target mobile i in the home cell can be written as

$$\gamma_i=\frac{LP_r}{I_{\rm od}+I_{\rm sd}+I_{\rm ic}+\eta} \tag{7}$$

where L is the processing gain and η is the white thermal noise power. In Section III, we will further derive the expression of γ_i with consideration of the effect of antenna beamforming.

III. Interference Analysis With Beamforming

In this section, we investigate how antenna beamforming can improve the performance of TDD/CDMA systems. We consider the conventional beam-steering method and the MVDR beamformer. The reasons why these two beamformers are studied in this paper are explained as follows. From the viewpoint of implementation, the beam-steering technique is the most economical and practical solution because of its simplicity. In [14], the authors demonstrated that remarkable capacity gain can be achieved for FDD/CDMA systems by using this kind of beamformer. In this paper, the beam-steering technique is evaluated to provide the baseline performance for comparison. As for the MVDR beamformer, it is well known for its capability of suppressing strong interference [17]. In [18], it is shown that the MVDR criterion can lead to the optimal solution in the sense of maximizing the output signal-to-interference-plus-noise ratio (SINR). Thus, in our paper, the MVDR beamformer is evaluated to give a performance upper bound for the TDD/CDMA system with antenna beamforming techniques.

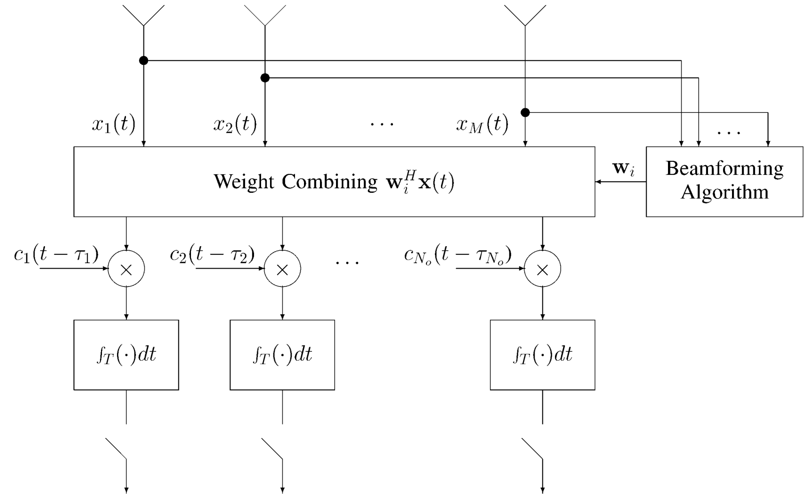


Fig. 3. Receiver block diagram with antenna beamformers.

A. Generic Interference Analysis

To begin with, we first derive the expression of the received bit energy-to-interference density ratio with a generic antenna beamformer. Assume that an M-element uniform circular array (UCA) is employed at a base station. The array manifold vector (or steering vector) of an UCA is written as [17]

$$\mathbf{a}(\theta,\phi)=\frac{1}{\sqrt{M}}\begin{bmatrix} e^{j2\pi l/\lambda \sin\phi\cos\theta} \\ e^{j2\pi l/\lambda \sin\phi\cos(\theta-2\pi/M)} \\ \vdots \\ e^{j2\pi l/\lambda \sin\phi\cos(\theta-2\pi(M-1)/M)} \end{bmatrix} \tag{8}$$

where l is the radius of the circular antenna array, λ the wavelength, θ the azimuth angle, and ϕ the vertical angle. The factor $1/\sqrt{M}$ in (8) is a normalization factor such that $\mathbf{a}^H\mathbf{a}=1$, where $[\cdot]^H$ denotes the complex transpose conjugate. In this paper, we assume that l is equal to half the wavelength and the vertical angle ϕ is equal to $\pi/2$.

Let $\mathbf{x}(t)=[x_1(t),x_2(t),\ldots,x_M(t)]^T$ be the received signal vector at an M-element antenna array. Then, $\mathbf{x}(t)$ can be written as

$$\mathbf{x}(t)=\mathbf{x}_i(t)+\mathbf{x}_{\text{od}}(t)+\mathbf{x}_{\text{sd}}(t)+\mathbf{x}_{\text{ic}}(t)+\mathbf{n}(t) \tag{9}$$

where $\mathbf{x}_i(t)$ is the desired signal for user i, $\mathbf{x}_{\text{od}}(t)$ is the opposite-direction interference, $\mathbf{x}_{\text{sd}}(t)$ is the same-direction interference, $\mathbf{x}_{\text{ic}}(t)$ is the intracell interference, and $\mathbf{n}(t)$ is the white noise. Specifically, $\mathbf{x}_{\text{od}}(t)$ in (9) is given by

$$\mathbf{x}_{\text{od}}(t)=\sum_{k\in\mathcal{B}_{\text{od}}}\sqrt{P_T G(d_k,\alpha_k)}\mathbf{b}_k \tag{10}$$

where $\mathbf{b}_k$ is the array manifold vector for the signals arriving from cell k ($k\in\mathcal{B}_{\text{od}}$). Meanwhile, $\mathbf{x}_{\text{sd}}(t)$, $\mathbf{x}_{\text{ic}}(t)$, and $\mathbf{x}_i(t)$ can be expressed, respectively, as

$$\mathbf{x}_{\text{sd}}(t)=\sum_{k\in\mathcal{B}_{\text{sd}}}\sum_{i_k=1}^{N_k}\sqrt{P_r\beta_{i_k}}u_{i_k}\left(\left\lfloor\frac{t-\tau_{i_k}}{T}\right\rfloor\right) \times c_{i_k}(t-\tau_{i_k})\mathbf{a}_{i_k} \tag{11}$$

$$\mathbf{x}_{\text{ic}}(t)=\sum_{i_0\neq i}^{N_0}\sqrt{P_r}u_{i_0}\left(\left\lfloor\frac{t-\tau_{i_0}}{T}\right\rfloor\right)c_{i_0}(t-\tau_{i_0})\mathbf{a}_{i_0} \tag{12}$$

and

$$\mathbf{x}_i(t)=\sqrt{P_r}u_i\left(\left\lfloor\frac{t-\tau_i}{T}\right\rfloor\right)c_i(t-\tau_i)\mathbf{a}_i. \tag{13}$$

In (11)–(13), $\mathbf{a}_{i_k}$ is the array manifold vector for the signals arriving from mobile i_k of cell k, $u_{i_k}(\cdot)$ is the bit waveform with a period T, τ_{i_k} is the propagation delay, $c_{i_k}(\cdot)$ is the spreading code, and P_r and β_{i_k} are already defined in (3) and (4).

Fig. 3 shows the receiver block diagram of an antenna beamformer. In Fig. 3, the received signal $\mathbf{x}(t)$ for a target user i ($i=1,\ldots,N_0$) is first combined with the beamformer weights $\mathbf{w}_i$. After weight combining, the output signal $\mathbf{w}_i^H\mathbf{x}(t)$ is connected to the despreader with processing gain L. Assume that the code sequences of different users are mutually uncorrelated. Then, the opposite-direction interference I_{od} in (2), the same-direction interference I_{sd} in (5), and the intracell interference I_{ic} in (6) become

$$I_{\text{od}}=\sum_{k\in\mathcal{B}_{\text{od}}}P_T G(d_k,\alpha_k)\left\|\mathbf{w}_i^H\mathbf{b}_k\right\|^2 \tag{14}$$

$$I_{\text{sd}}=\sum_{k\in\mathcal{B}_{\text{sd}}}\sum_{i_k=1}^{N_k}P_r\beta_{i_k}\left\|\mathbf{w}_i^H\mathbf{a}_{i_k}\right\|^2 \tag{15}$$

and

$$I_{\text{ic}}=\sum_{i_0\neq i}^{N_0}P_r\left\|\mathbf{w}_i^H\mathbf{a}_{i_0}\right\|^2 \tag{16}$$

respectively.

By substituting (14)–(16) into (7), the bit energy-to-interference density ratio of mobile i with antenna beamforming becomes

$$\gamma_i=LP_r\left\{\sum_{k\in\mathcal{B}_{\text{od}}}P_T G(d_k,\alpha_k)\left\|\mathbf{w}_i^H\mathbf{b}_k\right\|^2+\sum_{k\in\mathcal{B}_{\text{sd}}}\sum_{i_k=1}^{N_k}P_r \cdot\beta_{i_k}\|\mathbf{w}_i^H\mathbf{a}_{i_k}\|^2+\sum_{i_0\neq i}^{N_0}P_r\|\mathbf{w}_i^H\mathbf{a}_{i_0}\|^2+\eta\right\}^{-1}. \tag{17}$$

Next, we will investigate the effect of two specific beamformer algorithms, i.e., the beam-steering method and the MVDR beamformer.

B. Conventional Beam-Steering Technique (Scheme I)

Scheme I adopts the conventional beam-steering algorithm. According to the beam-steering method, we know that the beamformer weight $\mathbf{w}_{\rm bs}$ for user i is equal to its array manifold vector [17], i.e.,

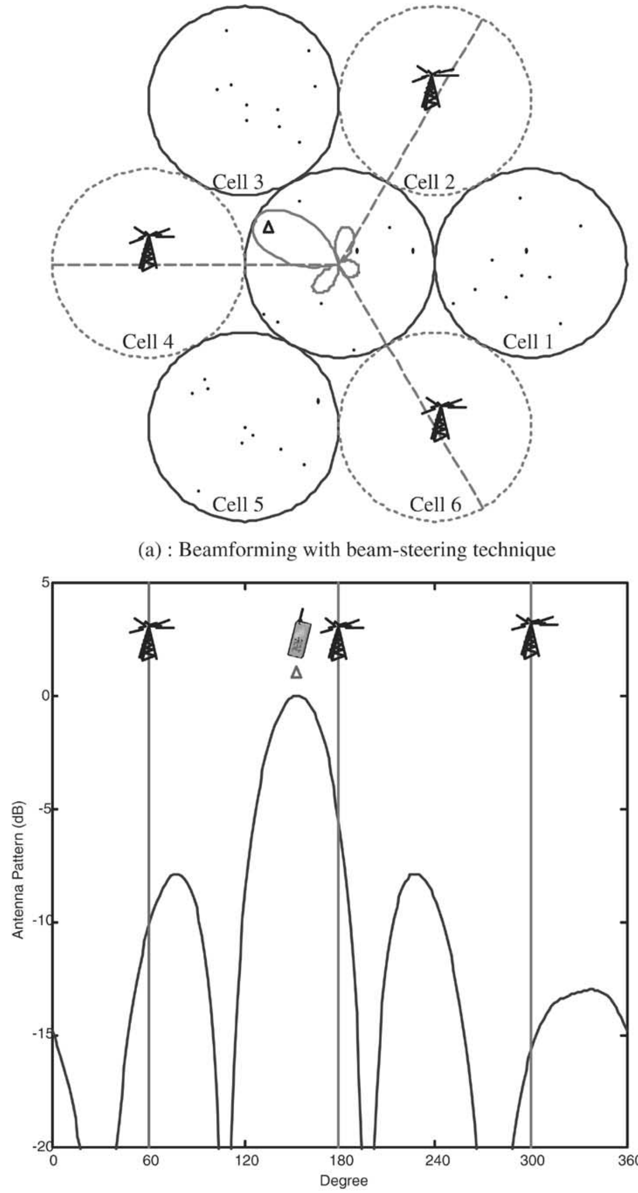
$$\mathbf{w}_{\rm bs} = \mathbf{a}_i \tag{18}$$

where $\mathbf{a}_i$ is defined in (8). As a result, the bit energy-to-interference density ratio after applying beam-steering (denoted as $\gamma_{\rm bs}$) becomes

$$\gamma_{\rm bs} = LP_r \left\{ \sum_{k\in\mathcal{B}_{\rm od}} P_T G(d_k,\alpha_k) \left\|\mathbf{a}_i^H \mathbf{b}_k\right\|^2 + \sum_{k\in\mathcal{B}_{\rm sd}} \sum_{i_k=1}^{N_k} P_r \cdot \beta_{i_k} \left\|\mathbf{a}_i^H \mathbf{a}_{i_k}\right\|^2 + \sum_{i_0\neq i}^{N_0} P_r \left\|\mathbf{a}_i^H \mathbf{a}_{i_0}\right\|^2 + \eta \right\}^{-1}. \tag{19}$$

The effect of utilizing the conventional beam-steering technique (Scheme I) is equivalent to steering a beam of signals concentrating at the desired direction. By controlling the direction of the receiving beam to track the position of the target mobile station, the beam-steering technique can reduce the effective interference thanks to a lesser number of interferers falling within the angle of the established receiving beam. Assume that the interfering mobiles are uniformly distributed in a cell and that W is the effective beamwidth in radian formed by the beam-steering technique. Then, the terms $\left\|\mathbf{a}_i^H \mathbf{b}_k\right\|^2$ and $\left\|\mathbf{a}_i^H \mathbf{a}_{i_k}\right\|^2$ in (19) can be approximated by a Bernoulli random variable with a successful probability $W/2\pi$. Because the opposite-direction interference $I_{\rm od}$ and the same-direction interference $I_{\rm sd}$ are reduced by the factors $\|\mathbf{a}_i^H \mathbf{b}_k\|^2$ and $\|\mathbf{a}_i^H \mathbf{a}_{i_k}\|^2$, respectively, the received $\gamma_{\rm bs}$ can be improved.

It has been demonstrated that the beam-steering method can significantly improve the performance of FDD/CDMA systems [14]. However, we conjecture that this kind of beam-steering technique may not be good enough to suppress the opposite-direction interference in the TDD/CDMA system. Take Fig. 4 as an example. Fig. 4(a) and (b) illustrate a beam pattern formed by the beam-steering technique from the viewpoints of the whole system and the antenna beam pattern, respectively. In this figure, a triangle-shaped target mobile is located in the center cell. Cells 2, 4, and 6 surround the center cell and generate the opposite-direction interference. From Fig. 4(b), one can see that the conventional beamformer can establish a narrow beam pattern directing toward the target mobile at the angle of 150°. However, this beamformer can only reduce the impact of the opposite-direction interference by smaller antenna gains ranged from 10, 5.6, and 16 dB at the angles of 60°, 180°, and 300°, respectively. Therefore, the beam pattern of Scheme I may not be good enough to resolve the opposite-direction interference issue for TDD/CDMA systems. This is because the beam-steering technique only directs the main beam toward the desired mobile instead of suppressing the opposite-direction interference from the side lobe. Based on this observation, in the TDD/CDMA system we prefer the MVDR beamformer to the beam-steering technique.



(a) : Beamforming with beam-steering technique

(b) : Antenna pattern with beam-steering technique

Fig. 4. Illustrative example for a TDD/CDMA system with Scheme I, where the home cell employs beam-steering at the base station. In this example, there are three adjacent cells ($\mathcal{B}_{\rm od}$ =2, 4, 6) generating the opposite-direction interference to the center cell.

C. MVDR Beamformer (Scheme II)

It is well known that the MVDR beamformer can direct the main receiving beam toward the desired user, while cancelling the strong interference simultaneously. Therefore, we expect that the MVDR beamformer is more suitable to resolve the issue of the opposite-direction interference in the TDD/CDMA system compared with the conventional beam-steering technique. In the following, we will incorporate the effect of the MVDR beamformer into the analysis of the uplink received signals in the TDD/CDMA system.

The goal of the MVDR criteria is to minimize the output power, while maintaining signal strength equal to one in the desired direction. That is, the MVDR beamformer will determine

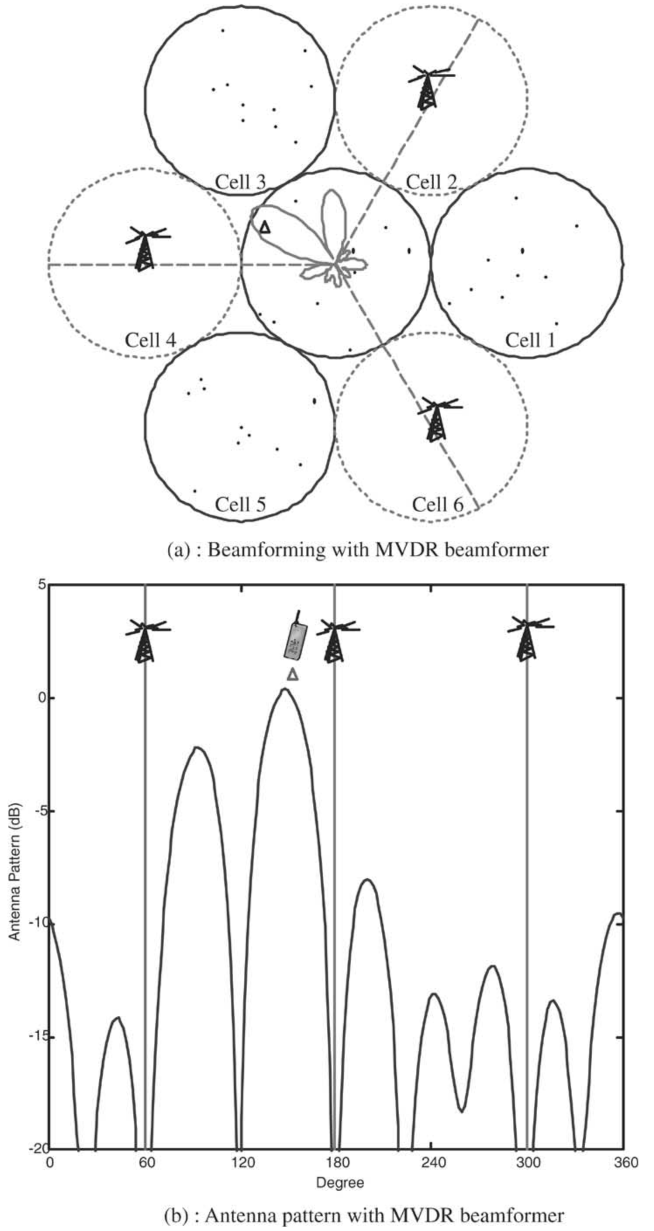


Fig. 5. Illustrative example for a TDD/CDMA system with Scheme II, where the home cell employs the MVDR beamformer at the base station. In this example, there are three adjacent cells ($\mathcal{B}_{\rm od} = \{2,4,6\}$) generating the opposite-direction interference.

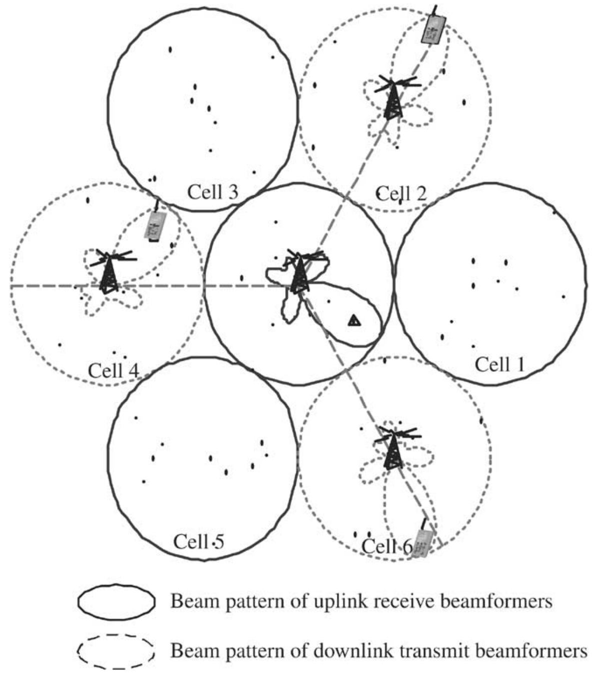


Fig. 6. Illustrative example for a TDD/CDMA system with Scheme III, where the beam pattern in the center cell is for the uplink reception and those in the neighboring cells $\mathcal{B}_{\rm od}$ =2, 4, 6 are for the downlink transmission.

the weight factor $\mathbf{w}_{\rm mv}$ of the combining scheme according to the following criteria:

$$\mathbf{w}_{\rm mv} = \arg\min_{\mathbf{w}_i} E\left\{\left\|\mathbf{w}_i^H\mathbf{x}\right\|^2\right\}$$
$$\text{s.t.} \quad \mathbf{w}_i^H\mathbf{a}_i = 1. \tag{20}$$

In (20), the term $E\left\{\left\|\mathbf{w}_i^H\mathbf{x}\right\|^2\right\}$ can be expressed as

$$E\left\{\left\|\mathbf{w}_i^H\mathbf{x}\right\|^2\right\} = \mathbf{w}_i^H\Phi_x\mathbf{w}_i \tag{21}$$

where Φ_x is the sampled covariance matrix of the received signal $\mathbf{x}(t)$, i.e., $\Phi_x = E\{\mathbf{x}(t)\mathbf{x}(t)^H\}$. Referring to (9), Φ_x can be written as

$$\Phi_x = P_r\mathbf{a}_i\mathbf{a}_i^H + \Phi_{\rm od} + \Phi_{\rm sd} + \Phi_{\rm ic} + \eta\mathbf{I} \tag{22}$$

where

$$\Phi_{\rm od} = \sum_{k\in\mathcal{B}_{\rm od}} P_T G(d_k,\alpha_k)\mathbf{b}_k\mathbf{b}_k^H \tag{23}$$

$$\Phi_{\rm sd} = \sum_{k\in\mathcal{B}_{\rm sd}}\sum_{i_k=1}^{N_k} P_r\beta_{i_k}\mathbf{a}_{i_k}\mathbf{a}_{i_k}^H \tag{24}$$

and

$$\Phi_{\rm ic} = \sum_{i_0\neq i}^{N_0} P_r\mathbf{a}_{i_0}\mathbf{a}_{i_0}^H. \tag{25}$$

Here, $\Phi_{\rm od}$, $\Phi_{\rm sd}$, and $\Phi_{\rm ic}$ denote the signal covariance matrices of the opposite-direction, same-direction, and intracell interferences, respectively.

Applying the Lagrange multiplier approach, one can obtain the MVDR beamformer weight $\mathbf{w}_{\rm mv}$ as [17]

$$\mathbf{w}_{\rm mv} = \frac{\Phi_x^{-1}\mathbf{a}_i}{\mathbf{a}_i^H\Phi_x^{-1}\mathbf{a}_i}. \tag{26}$$

According to [17], the total output power after the MVDR beamforming is equal to

$$E\left\{\left\|\mathbf{w}_{\rm mv}^H\mathbf{x}\right\|^2\right\} = \left(\mathbf{a}_i^H\Phi_x^{-1}\mathbf{a}_i\right)^{-1}. \tag{27}$$

Then, similar to the derivation of (19), we can first substitute the weight $\mathbf{w}_{\rm mv}$ of (26) into (17) and then refer to (27) to obtain

TABLE I
SYSTEM PARAMETERS

Processing gain	$L = 128$
COST-231 propagation model	$10\log(\kappa_0) = -128.1$, $m = 3.76$
Shadowing standard deviation	$\sigma = 8$ dB
Cell radius	$R = 1$ Km
Total transmit power of a base station	$P_T = 8$ W
Base station transmit power allocated for each mobile	$p_{i_k} = 0.4$ W
Thermal noise	$\eta = -112$ dBm
Power control level	$P_r/\eta = -1$ dB [5]

the bit energy-to-interference density ratio $\gamma_{\rm mv}$ with the MVDR beamformer (Scheme II) as

$$\gamma_{\rm mv} = \frac{LP_r}{\left(\mathbf{a}_i^H \Phi_x^{-1} \mathbf{a}_i\right)^{-1} - P_r}. \quad (28)$$

Comparing (22) and (28), we can further simplify $\gamma_{\rm mv}$ as

$$\gamma_{\rm mv} = L\left(\mathbf{a}_i^H \Phi_i^{-1} \mathbf{a}_i\right) \quad (29)$$

where

$$\Phi_i = \frac{(\Phi_{\rm od} + \Phi_{\rm sd} + \Phi_{\rm ic} + \eta\mathbf{I})}{P_r}. \quad (30)$$

In (30), Φ_i represents the normalized covariance matrix of the received interference-plus-noise signals.

Since it is not easy to further derive the closed-form expression for $\gamma_{\rm mv}$, we will evaluate $\gamma_{\rm mv}$ numerically to demonstrate the advantage of using the MVDR beamformer in TDD/CDMA systems later in Section V. Now, we use Fig. 5 to intuitively explain why the MVDR beamformer outperforms the beam-steering technique in TDD/CDMA systems. Fig. 5(a) and (b) shows a beam pattern of the MVDR beamformer with the same scenario as Fig. 4. Compared to Fig. 4, one can observe that the MVDR beamformer not only directs the beam toward the target mobile at the angle of 150°, but also nullifies the opposite-direction interference at the arrival angles of 60°, 180°, and 300°. Note that to obtain the weights of the MVDR beamformer, it only requires the knowledge of the direction of arrival (DoA) from the target mobile. In our work, we assume that the information of DoA of the target mobile is available, which can be obtained by the DoA estimation algorithms, such as in [13] and [19].

The superiority of MVDR beamforming in suppressing strong interference requires that the signal and interference are uncorrelated. In the multipath environment, the correlation between the desired signal and its multipath arrivals (regarded as interference) may seriously degrade the output signal-to-interference ratio performance. Several techniques to desensitize the correlation of the signal and interference in the received covariance matrix can be found in [19]. Fortunately, in the CDMA system, the delayed arrivals of the desired signal can be resolved by temporal filtering of RAKE receivers. Thus, using a two-dimensional (2-D) spatial-temporal architecture with each branch for an individual delayed path, the MVDR algorithm can still work well and even capture more energy of the desired signal in the multipath environment [20], [22], [23].

IV. DOWNLINK BEAMFORMING

In this section, we discuss how to improve the performance of the TDD/CDMA system further by exploiting the synergy of adopting both the downlink transmitting and uplink receiving beamforming simultaneously. Note that in TDD systems, due to channel reciprocity between the downlink and uplink, downlink beamforming can be implemented easily by taking advantage of the estimated parameters from uplink signals. The benefits of incorporating downlink transmitting beamforming can be illustrated by an example shown in Fig. 6. In this figure, the beam pattern of the center cell is for the uplink reception, while the beam patterns of the neighboring cells are for the downlink transmission. Assume that a simple downlink beam-steering technique has been adopted at the base stations of cells 2, 4, and 6. Obviously, the impacts of the opposite-direction interference signals from cells 2, 4, and 6 are alleviated because of weaker power radiating toward the direction of the home cell.

A. Joint Downlink and Uplink Beam-Steering (Scheme III)

Now we evaluate the effect of Scheme III, where the beam-steering method is adopted for both the downlink transmission and uplink reception at base stations. With downlink transmitting beamforming, the opposite-direction interference $\tilde{\mathbf{x}}_{\rm od}(t)$ [2] introduced by the neighboring cells can be modified from (10). That is

$$\tilde{\mathbf{x}}_{\rm od}(t) = \sum_{k\in\mathcal{B}_{\rm od}} \sum_{i_k=1}^{\tilde{N}_k} \sqrt{p_{i_k} G(d_k,\alpha_k)} \left\|\tilde{\mathbf{w}}_{i_k}^H \tilde{\mathbf{b}}_k\right\| \times u_{i_k}\left(\left\lfloor \frac{t-\tau_{i_k}}{T}\right\rfloor\right) c_{i_k}(t-\tau_{i_k})\mathbf{b}_k \quad (31)$$

where $\tilde{\mathbf{b}}_k$ is the array manifold vector of the signal transmitting from cell k ($k \in \mathcal{B}_{\rm od}$), $\tilde{\mathbf{w}}_{i_k}$ is the downlink beamformer weight of mobile i_k, $\tilde{N}_k$ is the number of mobile users in the downlink cycle, and p_{i_k} is the transmission power allocated to the mobile i_k from a base station. Then, the opposite-direction interference $I_{\rm od}$ at the output of the receive beamformer can be modified from (14) as

$$\tilde{I}_{\rm od} = \sum_{k\in\mathcal{B}_{\rm od}} \sum_{i_k=1}^{\tilde{N}_k} p_{i_k} G(d_k,\alpha_k) \left\|\tilde{\mathbf{w}}_{i_k}^H \tilde{\mathbf{b}}_k\right\|^2 \left\|\mathbf{w}_i^H \mathbf{b}_k\right\|^2. \quad (32)$$

Note that $P_T = \sum_{i_k=1}^{\tilde{N}_k} p_{i_k}$ is the total transmitter power of a base station. Comparing (32) with (14), one can observe that

[2] We add a word about notations. When $\tilde{[\cdot]}$ is used as superscripts, they denote the case when downlink beam-steering is applied.

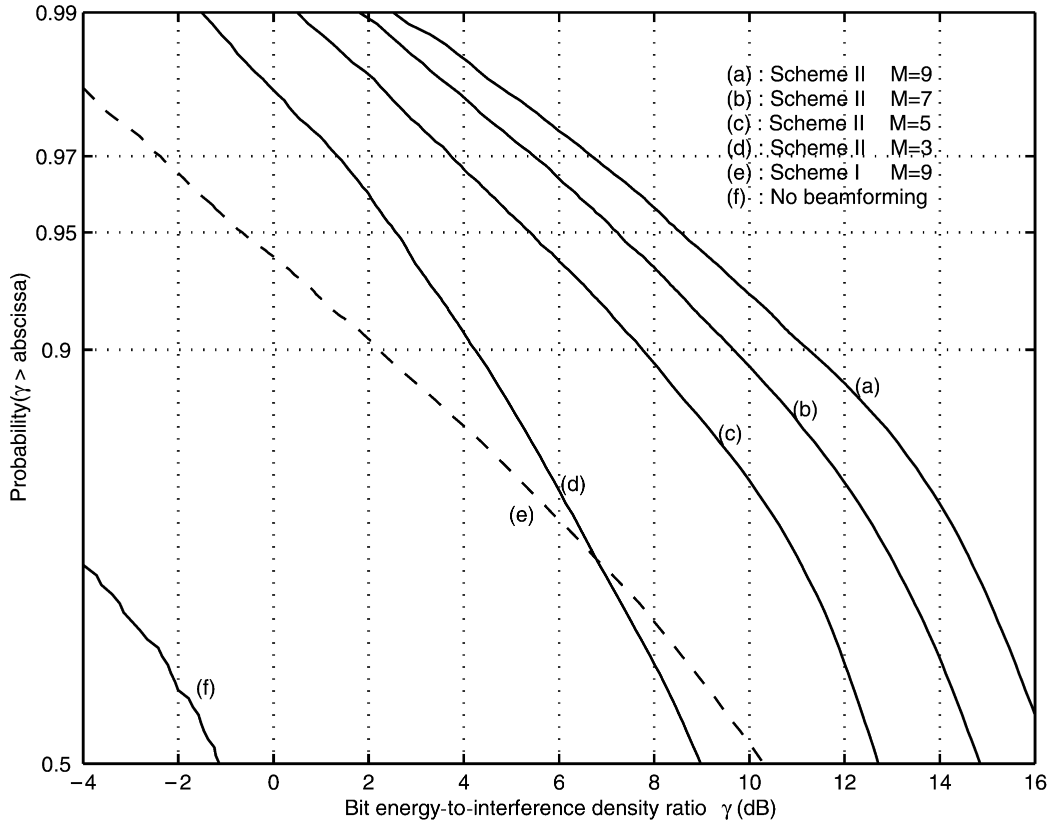


Fig. 7. Uplink performance comparison of Schemes I and II with different numbers of antenna elements (denoted as M). Note that, in this case, the number of cells generating the opposite-direction interference is equal to three.

after incorporating downlink transmitting beamforming, the effective radiation power that causes the opposite-direction interference from cell k $(k \in \mathcal{B}_{\rm od})$ can be reduced from P_T to a smaller value

$$\tilde{P}_T = \sum_{i_k=1}^{\tilde{N}_k} p_{i_k} \left\| \tilde{\mathbf{w}}_{i_k}^H \tilde{\mathbf{b}}_k \right\|^2. \tag{33}$$

From (18), we know that the downlink beamformer weight for mobile i_k of cell k $(k \in \mathcal{B}_{\rm od})$ is given by

$$\tilde{\mathbf{w}}_{i_k} = \tilde{\mathbf{a}}_{i_k} \tag{34}$$

where $\tilde{\mathbf{a}}_{i_k}$ is the array manifold vector of the signal transmitting from cell k to its serving mobile i_k $(k \in \mathcal{B}_{\rm od})$. Due to the reciprocity of TDD channels, $\tilde{\mathbf{a}}_{i_k}$ can be approximated by modifying $\mathbf{a}_{i_k}$, which is already obtained in the uplink beamforming. Replacing P_T of (19) with the effective radiated power $\tilde{P}_T$ of (33), we can obtain the bit energy-to-interference density ratio $\tilde{\gamma}_{\rm bs}$ of Scheme III as

$$\tilde{\gamma}_{\rm bs} = LP_r \left\{ \sum_{k \in \mathcal{B}_{\rm od}} \sum_{i_k=1}^{\tilde{N}_k} p_{i_k} G(d_k, \alpha_k) \left\| \tilde{\mathbf{a}}_{i_k}^H \tilde{\mathbf{b}}_k \right\|^2 \times \left\| \mathbf{a}_i^H \mathbf{b}_k \right\|^2 + \sum_{k \in \mathcal{B}_{\rm sd}} \sum_{i_k=1}^{N_k} P_r \beta_{i_k} \left\| \mathbf{a}_i^H \mathbf{a}_{i_k} \right\|^2 + \sum_{i_0 \neq i}^{N_0} P_r \left\| \mathbf{a}_i^H \mathbf{a}_{i_0} \right\|^2 + \eta \right\}^{-1}. \tag{35}$$

B. Joint Downlink Beam-Steering and Uplink MVDR Beamformer (Scheme IV)

In the following, we derive the bit energy-to-interference density ratio $\tilde{\gamma}_{\rm mv}$ for Scheme IV. In Scheme IV, a base station transmits downlink signals through the beam-steering process, while in the uplink reception the MVDR beamformer is applied. Let $\tilde{\Phi}_{\rm od}$ represent the signal covariance matrix of the opposite-direction interference. Then, $\tilde{\Phi}_{\rm od}$ can be obtained by replacing P_T of (23) with $\tilde{P}_T$ of (33). That is

$$\tilde{\Phi}_{\rm od} = \sum_{k \in \mathcal{B}_{\rm od}} \sum_{i_k=1}^{\tilde{N}_k} p_{i_k} G(d_k, \alpha_k) \left\| \tilde{\mathbf{w}}_{i_k}^H \tilde{\mathbf{b}}_k \right\|^2 \mathbf{b}_k \mathbf{b}_k^H \tag{36}$$

where $\tilde{\mathbf{w}}_{i_k} = \tilde{\mathbf{a}}_{i_k}$, as in (34). Substituting (36) into (30), we can obtain the normalized covariance matrix $\tilde{\Phi}_i$ of the total interference plus noise as

$$\tilde{\Phi}_i = \frac{(\tilde{\Phi}_{\rm od} + \Phi_{\rm sd} + \Phi_{\rm ic} + \eta \mathbf{I})}{P_r}. \tag{37}$$

Finally, replacing Φ_i of (29) with $\tilde{\Phi}_i$ of (37), we can obtain $\tilde{\gamma}_{\rm mv}$ for Scheme IV as

$$\tilde{\gamma}_{\rm mv} = L \left(\mathbf{a}_i^H \tilde{\Phi}_i^{-1} \mathbf{a}_i \right). \tag{38}$$

Note that in both Schemes III and IV, the conventional beam-steering technique is used for downlink transmitting beamforming. One may wonder why the MVDR beamforming is not applied in the downlink transmitting beamforming. We will discuss this issue in the following. Unlike the uplink

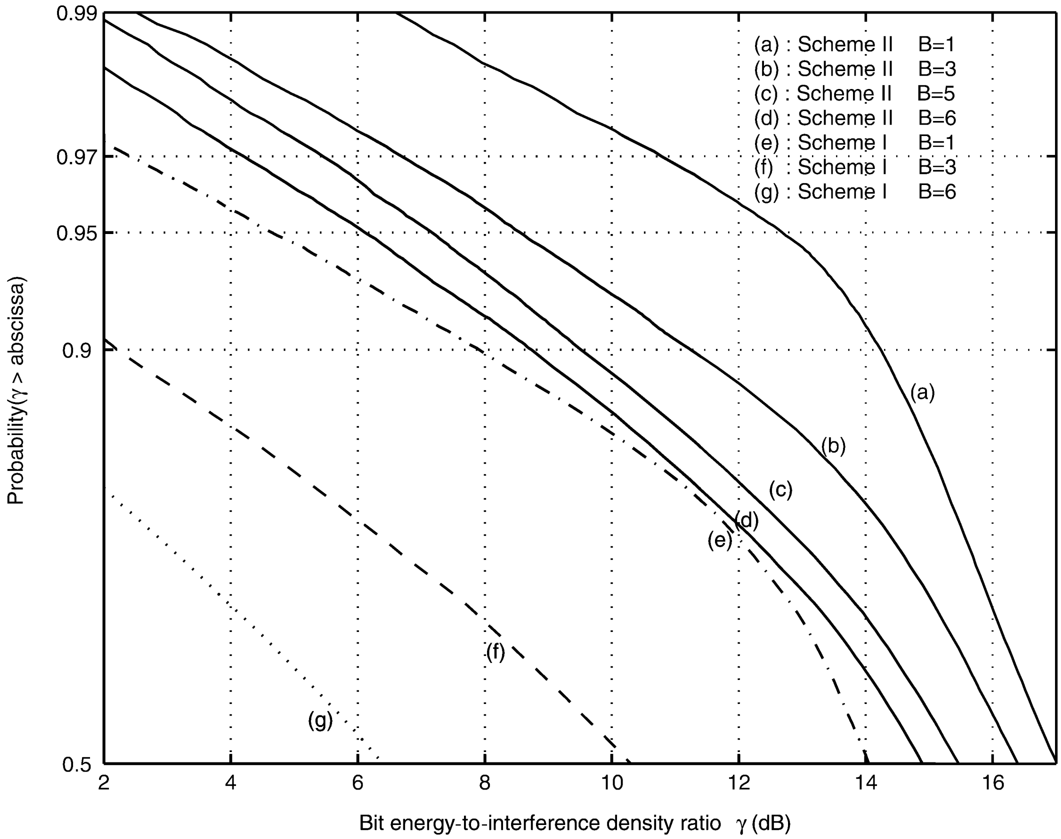


Fig. 8. Uplink performance comparison of Schemes I and II with different numbers of cells generating the opposite-direction interference (denoted as B). Note that, in this case, the number of antenna elements is equal to nine.

receiving beamformer, which does not impose any negative impacts on other users, the downlink transmitting beamformer may possibly exacerbate the downlink performance of other users. For example, consider the receiving MVDR beam pattern of Fig. 5, where the main beam is directing to the desired user at the angle of 150° and three nulls at the angles of 60°, 180°, and 300°. It is noteworthy that compared to the conventional beam-steering technique, the uplink MVDR beamformer place the nulls at the directions of interfering sources at the cost of increasing the magnitude of side lobes. Thus, because of higher amplitude in the side lobes, the downlink MVDR transmitting beamforming may cause strong interference to other mobiles, e.g., the mobile at the angle of 93° in Fig. 5. From this observation, we believe that it is not feasible to apply the weight obtained in the uplink MVDR beamforming straightforwardly for downlink transmitting beamforming. To determine the optimal weights of downlink transmitting beamforming is a complicated issue [15], [16] and beyond the scope of this paper. Here, we only consider the suboptimal beam-steering technique for downlink beamforming. In Section V, we will show that, even with this kind of simple downlink beam-steering technique, the performance of the TDD/CDMA system can be significantly improved.

V. Numerical Results

This section demonstrates the performance results of the four aforementioned different beamforming techniques. We consider a TDD/CDMA multicellular system, where all cells provide asymmetric traffic services based on their own traffic requirements. Through simulation, we evaluate the bit energy-to-interference density ratio γ for Schemes I–IV according to (19), (29), (35), and (38), respectively. The number of active users in every cell is set to 20 during one time slot, i.e., $N_k = \tilde{N}_k = 20$. In all simulations, we assume that mobiles are uniformly distributed and the other system parameters used in simulation are listed in Table I.

A. *Performance of Uplink Beamforming*

Fig. 7 compares the uplink performance of Schemes I and II. In Scheme I, beam-steering is applied to suppress the opposite-direction interference, while Scheme II adopts the MVDR beamformer. We define the reliability function p as the complementary cumulative distribution function (cdf) of γ, i.e., $p = 1-\text{Prob}\{\gamma \leq \gamma_{\text{th}}\}$, where γ_{th} is the required bit energy-to-interference density ratio. In the figure, curves (a)–(d) show the performances of the MVDR beamformer with different number of antenna elements, whereas curve (e) shows the performance of the beam-steering technique. For comparison, the performance without using any beamforming technique is shown in curve (f). In this figure and hereafter, $B = |\mathcal{B}_{\text{od}}|$ denotes the number of surrounding cells generating the opposite-direction interference. Let us focus on the case when $\gamma_{\text{th}} = 7$ dB and $p = 90\%$. From curves (a), (b), and (c), one can find that the uplink MVDR beamformer with antenna elements M =9, 7, and 5 can have satisfactory performance. Because in our simulation scenario there are three neighboring cells generating the strong opposite-direction interference, it is necessary to have at least four

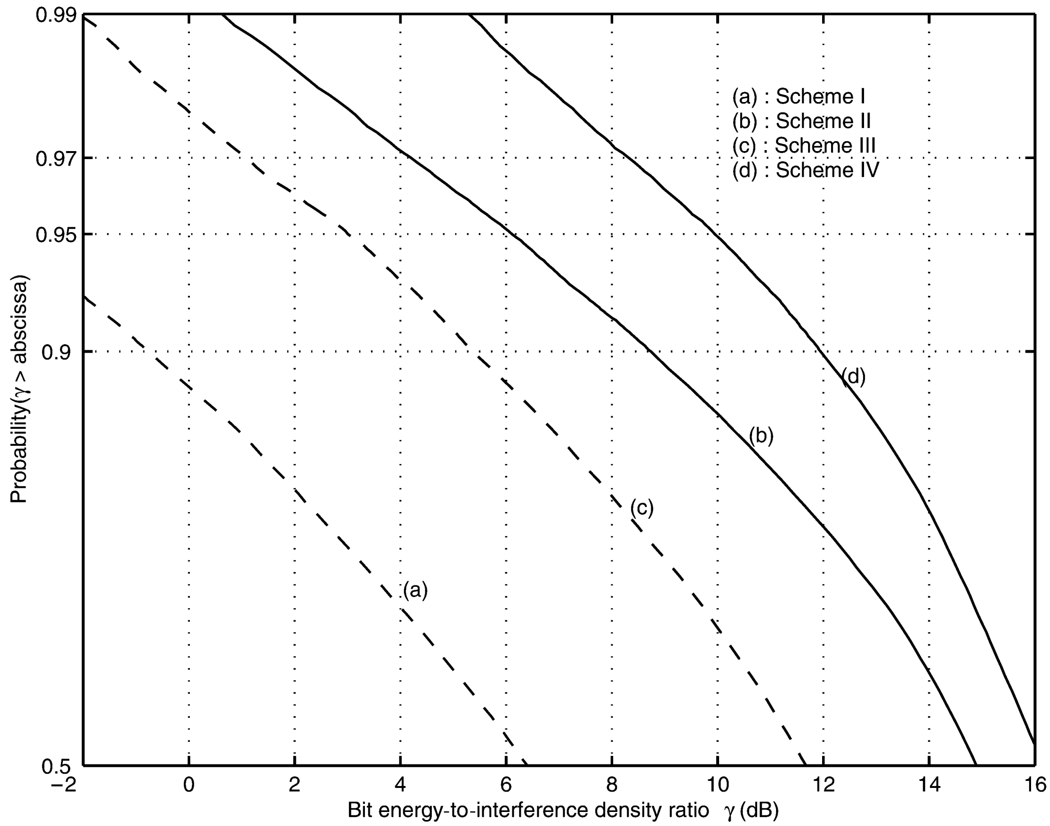


Fig. 9. Performance improvements by implementing downlink transmitting beamformer in the surrounding base stations, where the number of cells generating the opposite-direction interference equal to six and the number of antenna elements equal to nine.

antenna elements in the MVDR beamformer to place enough nulls to suppress the three strong interfering signals. By contrast, from curve (e) one can see that even with nine antenna elements, Scheme I still cannot yield any feasible solution to overcome the opposite-direction interference.

Fig. 8 compares the performances of Schemes I and II with different numbers of cells generating the opposite-direction interference. With nine antenna elements (M =9), curves (e)–(g) and (a)–(d) show the performances of Schemes I and II, respectively. Assume that the required reliability p is equal to 90%. We find that when we increase the number of neighboring cells generating the opposite-direction interference from one to three, the 90th percentile of γ in Scheme II degrades 3 dB, whereas in Scheme I the 90th percentile of γ degrades 6 dB. Thus, we can conclude that, as compared to the conventional beam-steering method, the MVDR beamformer is less sensitive to the increase of the number of cells generating the opposite-direction interference.

B. Performance of Downlink Beamforming

Fig. 9 demonstrates the performance improvements by adopting downlink transmitting beamforming. One can find that when the downlink transmitting beam-steering method is employed, both Schemes III and IV improve the performance of the TDD/CDMA system significantly as compared to Schemes I and II, respectively. Compared to Scheme II [curve (b)], Scheme IV can improve the 90th percentile of γ from 8.74 to 11.94 dB [curve (d)]. Note that Scheme IV adopts both the downlink transmitting beam-steering and uplink receiving MVDR beamformers, while Scheme II only utilizes the MVDR beamformer in the uplink reception. For Scheme I, the 90th percentile of γ is -0.76 dB [curve (a)], while for Scheme III the 90th percentile of γ is improved to 5.36 dB [curve (c)].

Fig. 10 demonstrates the impacts of the four aforementioned beamforming techniques in TDD/CDMA systems against the increase of the number of cells generating the opposite-direction interference. One can see that Scheme IV is least sensitive to the increase of the number of cells causing the opposite-direction interference. Let us consider the case when the required $\gamma_{\rm th}$ is equal to 7 dB. One can observe that the reliability function with Scheme IV is slightly degraded to 98% as B increases from zero to six. However, for Scheme III the reliability function is degraded to 84%. Note that Scheme II can also be an effective approach to suppress the opposite-direction interference since its reliability is still higher than 90%.

C. Discussion

To determine which beamforming scheme should be used in TDD/CDMA systems is a complicated tradeoff issue between performance improvements and implementation costs. Scheme IV, using the uplink MVDR beamforming and downlink transmitting beam-steering, can effectively suppress the opposite-direction interference, thereby providing greater flexibility in delivering asymmetric traffic services. In Scheme IV, every TDD/CDMA cell can *independently* designate traffic patterns for either uplink or downlink modes in every time slot according to its own rate of traffic asymmetry. On the other hand, using a simpler beam-steering method in both the uplink

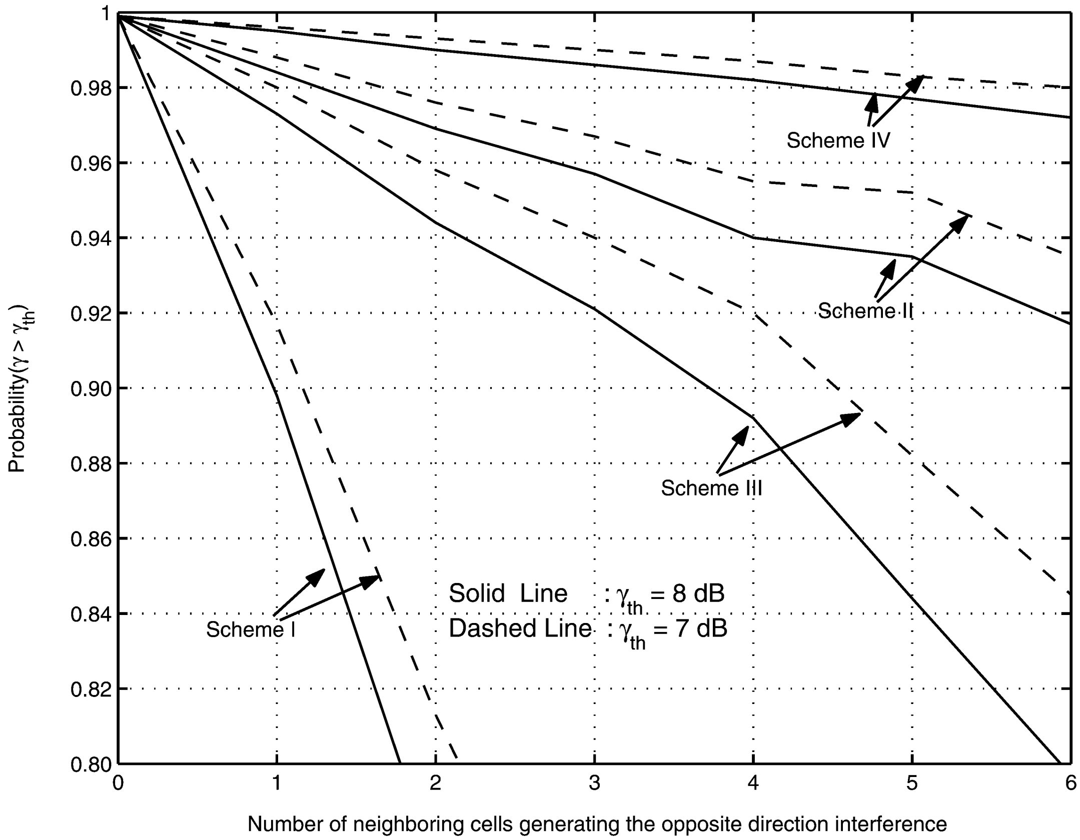


Fig. 10. Performance comparison of four beamforming schemes with different numbers of cells generating the opposite-direction interference, where an antenna array with nine elements is deployed at base stations.

reception and downlink transmission, Scheme III provides satisfactory performance only when the number of cells generating the opposite-direction interference is not large. Thus, it is suggested to combine Scheme III with other sectorization or channel-assignment techniques to reduce the number of cells generating the opposite-direction interference.

Scheme II is another effective technique to reduce the impact of the opposite-direction interference. Recall that Scheme II utilizes the MVDR beamforming only in the uplink. Note that the performance of Scheme II is better than Scheme III, but worse than Scheme IV. As remarked earlier, the extra cost of implementing downlink transmitting beam-steering may not be very high. If so, Scheme IV will be a better choice than Scheme II, provided that the MVDR beamformer has already been adopted in the uplink. As for Scheme I, it is shown that only using beam-steering in the uplink cannot provide acceptable performance.

Although in this paper we concentrate on the uplink performance of TDD/CDMA systems, antenna beamforming can also be exploited to improve the downlink performance. For example, by taking advantage of the reciprocity of TDD channels, downlink transmitting beamforming from neighboring base stations can lower the effective interfering power to the mobile station in the home cell. Furthermore, when the mobile station is employed with a small number of array sizes [24], [25], the downlink performance can be further enhanced with beamforming techniques similar to Schemes III and IV.

VI. Conclusion

In this paper, we have investigated the effects of beamforming techniques from the perspective of suppressing the opposite-direction interference to improve the uplink performance of TDD/CDMA systems. We exploit the synergy of combining the downlink transmitting and uplink receiving beamforming to search a feasible scheme to resolve the opposite-direction interference from a network viewpoint. Based on our numerical results, we can draw the following conclusions.

- Schemes IV, which adopts the MVDR beamformer in the uplink and the beam-steering in the downlink, can effectively suppress the strong opposite-direction interference of TDD/CDMA systems, thereby allowing every cell to provide asymmetric traffic services with different rates of traffic asymmetry.
- Scheme III, which adopts the beam-steering method in both the downlink transmission and uplink reception, can provide satisfactory performance when the number of cells generating the opposite-direction interference is not large. When combined with other sectorization or channel-assignment techniques, Scheme III can be a very effective mechanism to overcome the opposite-direction interference in the TDD/CDMA system with lower implementation costs.
- If only the uplink beamforming is considered, the MVDR beamformer (Scheme II) instead of the conventional

beamforming method (Scheme I) should be adopted since the conventional beam-steering can not effectively suppress the opposite-direction interference.

While we have sketched some potential advantages of using antenna beamforming to enhance the downlink performance of TDD/CDMA systems in Section V, it is still worthwhile to further investigate the downlink performance improvement in the future studies. In summary, this work has demonstrated the great potential of applying antenna beamforming techniques in the TDD/CDMA system. Even with the severe impact of the opposite-direction interference, we find that there exists a feasible and economical beamforming mechanism (e.g., Scheme III suggested in the paper), which can enable the TDD/CDMA system to deliver asymmetric traffic services within the entire service area with greater flexibility.

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