모바일 와이맥스 시스템에서 주변 셀의 신호 세기 정보를 이용한 인접 셀 간섭 감소 기법

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Mitigation of inter-cell interference using geometrical information in mobile WiMAX system

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Abstract

The Mobile-Worldwide Interoperability for Microwave Access (m-WiMAX) can provide wireless services at high rates even in high mobility. However, the performance of m-WiMAX can seriously be degraded near the cell boundary due to inter-cell interference (ICI). To mitigate the ICI problem in the downlink of m-WiMAX, we consider combined use of ICI mitigation techniques with macro beamforming to maximize the user capacity in response to the change of interference environment. The proposed scheme optimally determines the configuration of ICI mitigation techniques using the geometrical information (e.g., the long-term received signal strength of neighboring cells). Simulation results show that the proposed scheme can accurately estimate the user capacity and thus improve the capacity of users near the cell boundary.

1. Introduction

The Mobile-Worldwide Interoperability for Microwave Access (m-WiMAX or IEEE 802.16e) has been proposed to support wireless data services at high rates comparable to wire-line schemes such as the digital subscriber line (DSL) and it is being considered as a migration path toward next generation wireless systems [1]. Recently, a version of M-WiMAX, called WiBro, has been deployed in Korea.

The m-WiMAX considers the use of universal frequency reuse, yielding inter-cell interference (ICI) for the service of users near the cell boundary. In fact, the spectral efficiency in the worst channel condition can be reduced to one 120th of that in the best channel condition. As a consequence, to support real-time traffic at a rate of 512 kbps near the cell boundary, the m-WiMAX may need to allocate the whole downlink resource to a single user, which is unacceptable to service providers. Unless the m-WiMAX can significantly improve the spectral efficiency particularly near the cell boundary, it may not claim technological advantages over the incumbent 3G systems. Thus, the mitigation of ICI is one of the most impending problems in the m-WiMAX system.

A number of ICI mitigation techniques have been proposed for packet-based orthogonal frequency division multiple access (OFDMA) systems, including the use of interference avoidance (IA), interference randomization, interference cancellation and macro diversity [2]. IA schemes dynamically allocate the resource to avoid the ICI by exchanging the inter-cell information [3]. Fractional frequency reuse (FFR) techniques can avoid the ICI by preventing the target cell from using frequency resources used by adjacent cells [4]. However, they may limit the peak transmission rate due to the use of a reduced reuse factor. On the other hand, by cancelling out the ICI with the use of inter-cell channel state information (CSI), interference cancellation schemes can increase the carrier-to-interference power ratio (CIR) even in full loading environments [5]. Macro diversity originated from soft handoff in CDMA systems can provide a diversity gain [6].

Although the above conventional ICI mitigation techniques have their own pros and cons, their shortcomings can be alleviated with proper combined use of these techniques. Previous works considered the mitigation of ICI in the WiMAX system, but they did not consider combined use of these ICI mitigation techniques

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to get somewhat synergy effect [7]. In this paper, we consider combined use of ICI mitigation techniques to maximize the user capacity of the downlink near the cell boundary by simply using the geometrical information on the received signal strength (RSS) of neighbor cells. We also consider resource allocation according to the frequency reuse for IA in the partial usage of subchannels (PUSC) mode. Since the information between the sectors in a cell can be exchanged in real-time, we consider the use of intra-cell macro diversity. By making two sectors transmit the same signal, the receiver can obtain a RF combining or soft combining diversity gain [6]. However, it reduces the spectrum efficiency to one half due to reserved resources by the neighbor sector. To improve the spectrum efficiency, we propose the use of macro beamforming with coherent transmission via two sectors.

Following Introduction, Section 2 describes the system model in consideration and Section 3 describes the proposed macro beamforming based on uplink sounding, which is effective in the intra-cell handoff boundary. New strategies to mitigate the ICI in the m-WiMAX system are described in Section 4 and their performance is verified by computer simulation in Section 5. Finally, conclusions are given in Section 6.

2. System model

Consider an m-WiMAX system comprising N hexagonal cells each of which has three sectors. We assume that each sector uses two transmit antennas ($n_t = 2$) and MS uses two receive antennas ($n_r = 2$) [8]. When the target user is served by sector m of cell n, the received signal at subcarrier k can be represented by

$$\begin{aligned}\mathbf{y}(k) = \mathbf{H}_{n,m}(k)\mathbf{x}_{n,m}(k) + \sum_{i\neq m}\mathbf{H}_{n,i}(k)\mathbf{x}_{n,i}(k) \\ + \sum_{j\neq n}\sum_{i}\mathbf{H}_{j,i}(k)\mathbf{x}_{j,i}(k) + \mathbf{n}(k)\end{aligned} \quad (1)$$

where $\mathbf{x}_{j,i}$ is the $(n_t \times 1)$ signal vector of sector i of cell j, $\mathbf{n}$ is $(n_r \times 1)$ additive white Gaussian noise (AWGN) with power spectral density N_0 and $\mathbf{H}_{j,i}$ denotes the $(n_r \times n_t)$ channel matrix whose elements are assumed to have zero mean and variance given by

$$\sigma_{j,i}^2 = \frac{1}{n_r} E\left\{\text{trace}\left[\mathbf{H}_{j,i}(k)\mathbf{H}_{j,i}^*(k)\right]\right\} = 10^{0.1\left\{A(\theta_{j,i}) - PL(d_{j,i})\right\}}. \quad (2)$$

Here $E\{\bullet\}$ denotes the expectation, the superscript * denotes conjugate transpose, $PL\left(d_{j,i}\right)$ represents the path loss from sector i of cell j to the target user in decibel and $A(\theta)$ denotes the 3-sector antenna pattern specified by

$$A(\theta) = -\min\left(12\left(\frac{\theta}{\theta_{3dB}}\right)^2, 20\right) \text{ (dB)} \quad (3)$$

where θ is defined as the angle between the direction of interest and the boresight of the antenna, and θ_{3dB} denotes the 3dB beamwidth in degree.

We consider the resource allocation for IA in a subcarrier permutation mode, as illustrated in Fig. 1. Assuming the whole frequency resource is divided into three logical bands, F_0, F_1 and F_2, the frequency reuse set (FRS) can be defined as

$$\varphi_1 = \{m_0, m_1, m_2\}, \varphi_2 = \{m_0, m_1\}, \varphi_3 = \{m_0, m_2\}, \varphi_4 = \{m_0\} \quad (4)$$

where m_0, m_1 and m_2 denote the band index corresponding to m_0, $(m+1)\%3$ and $(m+2)\%3$, respectively. Here, '$a\%b$' denotes a modulo b (e.g., when $m = 2$, $\varphi_1 = \{2,0,1\}$, $\varphi_2 = \{2,0\}$, and etc.). For example, the reuse set φ_1 indicates the use of band F_{m_0}, F_{m_1} and F_{m_2} (i.e., corresponding frequency reuse ratio (FRR) is 1), and the reuse set φ_2 indicates the use of band F_{m_0} and F_{m_1} (i.e., FRR is 2/3). The divided frequency resources can be allocated to users according to the ICI condition. For example, when the MS in sector 0 receives strong interference from sector 2, the frequency resource in reuse set φ_2 can be allocated to users in sector 0 and 1, not to users in sector 2. If the MS in sector 0 receives strong interference from sector 1 and 2, the frequency resource in reuse set φ_4 (i.e., FRR is 1/3) can be allocated to users in sector 0, not to users in sector 1 and 2.

3. Macro Beamforming

Macro diversity can double the transmit power and diversity gain but not provide any transmit array gain. In this sector, we consider the use of macro beamforming to enhance the performance of users in the intra-cell handoff boundary region, which extends the antenna configuration from $(n_t \times n_r)$ to $(2n_t \times n_r)$. The uplink sounding signal transmitted near the sector boundary can be received at least by two sectors, enabling the use of multi-sector beamforming.

The received signal by macro beamforming from sector m and $\hat{m}$ can be represented by [14]

$$\begin{aligned}\mathbf{y}(k) &= \left(\mathbf{H}_{n,m}(k)\mathbf{w}_{n,m}(k) + \mathbf{H}_{n,\hat{m}}(k)\mathbf{w}_{n,\hat{m}}(k)\right)x + \mathbf{z}_k \\ &= \left[\mathbf{H}_{n,m}(k) \quad \mathbf{H}_{n,\hat{m}}(k)\right]\begin{bmatrix}\mathbf{w}_{n,m}(k) \\ \mathbf{w}_{n,\hat{m}}(k)\end{bmatrix} x + \mathbf{z}_k \\ &= \mathbf{H}_{n,(m,\hat{m})}\mathbf{w}_{n,(m,\hat{m})} + \mathbf{z}_k\end{aligned} \quad (5)$$

where $\mathbf{H}_{n,(m,\hat{m})}$ denotes the $(n_r \times 2n_t)$ channel matrix, $\mathbf{z}_k$ is the $(n_r \times 1)$ colored noise vector represented by

$$\mathbf{z}_k = \sum_{i\neq m,\hat{m}}\mathbf{H}_{n,i}(k)\mathbf{x}_{n,i} + \sum_{j\neq n}\sum_{i}\mathbf{H}_{j,i}(k)\mathbf{x}_{j,i} + \mathbf{n}(k) \quad (6)$$

with $E\{\mathbf{z}_k\mathbf{z}_z^*\} = \mathbf{K}_z \approx N_z\mathbf{I}_{n_r}$ and $\mathbf{w}_{n,(m,\hat{m})}$ is the $(2n_t \times 1)$ beamforming weight vector given by

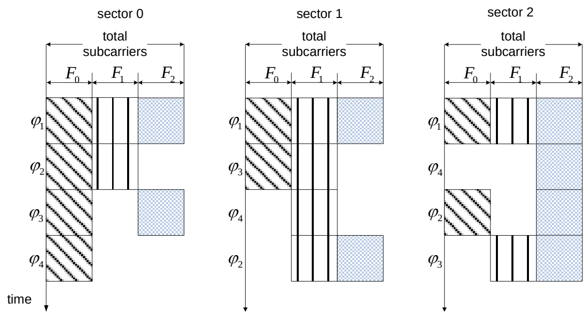

Fig. 1. Resource allocation according to the frequency reuse set

$$\mathbf{w}_{n,m} = \sqrt{2}\left[\tilde{\mathbf{h}}_{n,m}^{(1)} \quad \tilde{\mathbf{h}}_{n,\hat{m}}^{(1)}\right]^{*} \Big/ \left\|\left[\tilde{\mathbf{h}}_{n,m}^{(1)} \quad \tilde{\mathbf{h}}_{n,\hat{m}}^{(1)}\right]\right\|. \tag{7}$$

Here, $\tilde{\mathbf{h}}_{n,m}^{(1)}$ and $\tilde{\mathbf{h}}_{n,\hat{m}}^{(1)}$ are the $(1\times n_t)$ CSI vector of sector m and sector $\hat{m}$, respectively, of cell n obtained from the uplink sounding of the first antenna in the MS.

Macro beamforming has a transmit power constraint given by

$$E\left\{\mathrm{trace}\left[\mathbf{w}_{n,(m,\hat{m})}x_{n,m}\left(\mathbf{w}_{n,(m,\hat{m})}x_{n,m}\right)^{*}\right]\right\} = 2P_t \tag{8}$$

which can increase the carrier-to-interference-and-noise power ratio (CINR). Since the macro beamforming needs to reserve the corresponding resource of the neighboring sector, it reduces the spectrum efficiency by one half. These pros and cons of macro beamforming are similar to those of macro diversity. The difference between the two schemes is a degree of array gain.

The CINR of macro beamforming with post maximal ratio combining can be represented by [11]

$$\gamma \approx \frac{P_t}{N_z}\left(\left|\left[\mathbf{h}_{n,m}^{(1)} \quad \mathbf{h}_{n,\hat{m}}^{(1)}\right]\mathbf{w}_{n,(m,\hat{m})}\right|^2 + \left|\left[\mathbf{h}_{n,m}^{(2)} \quad \mathbf{h}_{n,\hat{m}}^{(2)}\right]\mathbf{w}_{n,(m,\hat{m})}\right|^2\right). \tag{9}$$

Since $\mathbf{h}_{n,m}^{(i)}$ and $\mathbf{h}_{n,\hat{m}}^{(i)}$ is a circularly symmetric Gaussian random vector with zero mean and variance $\sigma_{n,m}^2$, $\sigma_{n,\hat{m}}^2(\approx\sigma_{n,m}^2)$, respectively, it can be seen that $\left|\left[\mathbf{h}_{n,m}^{(1)} \quad \mathbf{h}_{n,\hat{m}}^{(1)}\right]\mathbf{w}_{n,(m,\hat{m})}\right|^2$ and $\left|\left[\mathbf{h}_{n,m}^{(2)} \quad \mathbf{h}_{n,\hat{m}}^{(2)}\right]\mathbf{w}_{n,(m,\hat{m})}\right|^2$ can be approximated as random variables $2\sigma_{n,m}^2\chi_{4n_t}^2$ and $2\sigma_{n,m}^2\chi_2^2$, respectively. Here χ_n^2 denotes a Chi-squared random variable with n degrees of freedom [10]. Therefore, the averaged post CINR is given by

$$\begin{aligned} E\left\{\gamma_{MBF}\right\} &\approx \frac{P_t\sigma_{n,m}^2}{N_z}\left(2E\left\{\chi_{4n_t}^2\right\} + 2E\left\{\chi_2^2\right\}\right) \\ &= \frac{P_t\sigma_{n,m}^2}{N_z}2\left(2n_t+1\right). \end{aligned} \tag{10}$$

Thus, the macro beamforming can maximally obtain an array gain which is 2.5 times over the macro diversity for (2×2) downlink MIMO.

4. Proposed ICI Mitigation Strategy

We consider a new ICI mitigation strategy that maximizes the capacity of users near the cell boundary with combined use of IA, interference cancellation and macro beamforming. Most of conventional ICI mitigation techniques only consider the amount of ICI. If the ICI environment (e.g., dominant inter-sector interference in its own cell and dominant interference from other cells) can be considered additionally, they may further increase the capacity.

Let $C_{s,j,c}$ be the user capacity associated with inter-sector cooperation utilizing two sectors, IA and interference cancellation, defined by [11]

$$C_{s,j,c} = E\left\{\upsilon_s\,\rho_j\,\log_2\left(1+\eta\gamma_{s,j,c}\right)\right\} \tag{11}$$

where s denotes a index related with inter-sector cooperation (e.g., 0, 1 and 2 denote 'not feasible', 'macro diversity' and 'macro beamforming', respectively), j denotes a reuse set index, c denotes a index indicating whether interference cancellation is feasible or not (i.e., 0 and 1 denote 'not feasible' and 'feasible', respectively), η is a parameter related to the implementation loss corresponding to CINR γ, ρ_j denotes the FRR given by

$$\rho_j = \begin{cases} 1 & j=1 \\ 2/3 & j=2,3 \\ 1/3 & j=4 \end{cases} \tag{12}$$

and υ_s denotes the sector reuse ratio given by

$$\upsilon_s = \begin{cases} 0.5, & s\neq 0 \\ 1, & s=0. \end{cases} \tag{13}$$

The main concern is to maximize the capacity of users near the cell boundary, given as

$$\begin{aligned} C_{\max} &= \max_{s,j,c} C_{s,j,c} \\ &\leq \max_{s,j,c} \upsilon_s\,\rho_j\,\log_2\left(1+\eta E\left\{\gamma_{s,j,c}\right\}\right). \end{aligned} \tag{14}$$

The average CINR $E\left\{\gamma_{s,j,c}\right\}$ can approximately be replaced by geometry $G_{s,j,c}$ as

$$E\left\{\gamma_{s,j,c}\right\} \approx G_{s,j,c} = \frac{P_{n,m}}{\sum\limits_{m'\in\varphi_j} S_{m'} - P_{n,\hat{m}}^{(IS)}(s,j) - P_{\dot{n},\dot{m}}^{(IC)}(s,j,c) + \sigma_z^2}\,g_{s,c} \tag{15}$$

where $P_{n,m}$ denotes the RSS of sector m of cell n as the serving sector, $S_{m'}$ denotes the interference from sector m' of all cells, φ_j denotes the reuse set of index j, $P_{n,\hat{m}}^{(IS)}(s,j)$ denotes the RSS of neighbor sector avoided by inter-sector cooperation, $P_{\dot{n},\dot{m}}^{(IC)}(s,j,c)$ denotes the RSS of sector $\dot{m}$ cell $\dot{n}$ to be cancelled by the receiver, σ_z^2 is the noise power level of the MS, and $g_{s,c}$ denotes the array gain of MIMO including the power gain.

The interference term $S_{m'}$ can be represented as

$$S_{m'} = \begin{cases} \sum_{n'=0,}^{N-1} P_{\cdot n',m'} - P_{n,m} & m' = m \\ \sum_{n'=0,}^{N-1} P_{n',m'} & m' \neq m. \end{cases} \quad (16)$$

$P^{(IS)}_{n,\hat{m}}(s, j)$ can be represented as

$$P^{(IS)}_{n,\hat{m}}(s, j) = \begin{cases} \max_{m' \in \{m_1, m_2\}} P_{n,m'} & s \neq 0,\ j=1 \\ P_{n,m_1} & s \neq 0,\ j=2 \\ P_{M \cdot n + m_2} & s \neq 0\ \ j=3 \\ 0 & \text{otherwise .} \end{cases} \quad (17)$$

$P^{(IC)}_{\hat{n},\hat{m}}(s, j, c)$ is associated with the interference cancellation method, the cell and its sector interfering at the maximum level to each reuse set except the serving sector, and the sector cooperating with macro antenna technique. It can be found by

$$P_{\hat{n},\hat{m}}(s, j, c) =$$
$$\begin{cases} \max_{1 \le n' \le N, m' \in \{m_0, m_1, m_2\}, \neq (n,m)} P_{n',m'} & c=1,\ j=1,\ s=0 \\ \max_{1 \le n' \le N, m' \in \{m_0, m_1, m_2\}, \neq (n,m), \neq (n,\hat{m})} P_{n',m'} & c=1,\ j=1,\ s \neq 0 \\ \max_{1 \le n' \le N, m' \in \{m_0, m_1\}, \neq (n,m)} P_{n',m'} & c=1,\ j=2,\ s=0 \\ \max_{1 \le n' \le N, m' \in \{m_0, m_1\}, \neq (n,m), \neq (n,\hat{m})} P_{n',m'} & c=1,\ j=2,\ s \neq 0 \\ \max_{1 \le n' \le N, m' \in \{m_0, m_2\}, \neq (n,m)} P_{n',m'} & c=1,\ j=3,\ s=0 \\ \max_{1 \le n' \le N, m' \in \{m_0, m_2\}, \neq (n,m), \neq (n,\hat{m})} P_{n',m'} & c=1,\ j=3,\ s \neq 0 \\ \max_{1 \le n' \le N, m' \in m, \neq (n,m)} P_{n',m'} & c=1,\ j=4 \\ 0 & \text{otherwise.} \end{cases} \quad (18)$$

Moreover, the necessary condition for the MS to estimate the CSI of the interfering sector is given by

$$P^{(IC)}_{\hat{n},\hat{m}}(s, j, c) = \begin{cases} P_{\hat{n},\hat{m}}(s, j, c) & \dfrac{P_{\hat{n},\hat{m}}(s, j, c)}{\sum_{m' \in \varphi_j} S_{m'} - P_{\hat{n},\hat{m}}(s, j, c) + \sigma_z^2} \ge T_{est} \\ 0 & \text{otherwise} \end{cases} \quad (19)$$

where T_{est} is a threshold of the CINR for the MS to estimate the CSI. We assume that the pilot pattern of the serving sector is orthogonal to that of an interfering sector by using cell-specific scrambling codes.

The array gain $g_{s,c}$ is associated with the macro antenna techniques and the feasibility of interference cancellation for given antenna technique. When interference cancellation is considered, the array gain is reduced by one half because the receive array gain can not be achieved [12]. Finally, we can maximize the user capacity (14) by finding a set of ICI mitigation techniques that maximizes the geometry capacity $\tilde{C}_{s,j,c}$, given by

$$\begin{aligned} \left(\hat{s}, \hat{j}, \hat{c}\right) &= \arg\max_{s,j,c} C_{s,j,c} \\ &\approx \arg\max_{s,j,c} \upsilon_s \rho_j \log_2\left(1 + \eta G_{s,j,c}\right) \\ &= \arg\max_{s,j,c} \tilde{C}_{s,j,c} \end{aligned} \quad (20)$$

5. Performance evaluation

We verify the performance of the proposed ICI mitigation scheme in the downlink of WiBro system by computer simulation. Table I summarizes the simulation parameters. We assume that the MS can obtain the CSI of the strongest interfering cell when its average CINR is larger than 0 dB as described in (19). For ease of verification, we also assume that the BS allocates resource to the MS at every frame time and the MS is served by sector 0. We consider two geographical regions to investigate severe interference environments where users in the sector boundary experience strong inter-sector interference from the same cell and users in the cell boundary experience strong ICI from other cells.

Fig. 2 (a) depicts the estimated geometry capacity corresponding to various sets combined with ICI mitigation techniques, which is obtained by using the RSS of neighbor cells. *FRS1*, *FRS2*, *FRS3* and *FRS4* denote resource allocation corresponding to each reuse set as illustrated in Section 2. It can be seen that set MB_FRS2, which combines macro beamforming for sector 1 of its own cell and IA (i.e., *FRS2*) for sector 2, outperforms other sets. Fig. 2 (b) depicts the user capacity when the link adaptation is performed at every frame with combined use of ICI mitigation techniques. It can be seen that the proposed scheme that maximizes the estimated capacity outperforms the use of pure IA and pure IC scheme [5].

Fig. 3 (a) depicts the estimated capacity when ICI mitigation techniques are jointly employed in the cell boundary region at an average CINR of -5dB.

TABLE I. Simulation parameters.

Parameters	Values
Number of 3-sector Cells	19
Carrier frequency	2.3 GHz
FFT Size	1024
Channel bandwidth	8.75 MHz
Sampling frequency	10MHz
Cell radius	1 km
Antenna scheme	Beamforming (BF)
Subcarrier allocatoin	PUSC
Path loss model	COST 231-Hata Suburban
BS antenna pattern	65°(-3dB)
Cell loading factor	1
Channel model	ITU-R Pedestrian A 3km/h
Channel estimation	Perfect
Receiver algorithm	Linear MMSE

It can be seen that combined use of IA (i.e., $FRS2, FRS3$) and interference cancellation yields the best performance in direction of 0°, the use of IA yields the best performance in direction of 30°, and combined use of macro beamforming and IA (i.e., $F_{1,2}$) yields the best performance in direction of 60°. It can be seen from Fig. 3 (b) that the proposed scheme outperforms the conventional schemes, pure IC and pure IA.

6. Conclusions

We have proposed a new ICI mitigation strategy that maximizes the capacity of users near the cell boundary. The proposed strategy optimally combines ICI mitigation techniques based on the geometrical information. We have considered additional use of macro beamforming to avoid strong inter-sector interference while obtaining the transmit array gain. The simulation results show that the proposed strategy can enhance the user capacity by adaptively employing ICI mitigation techniques.

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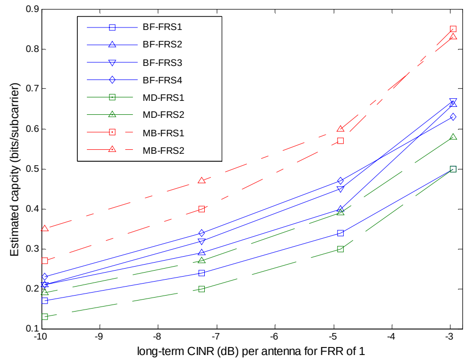
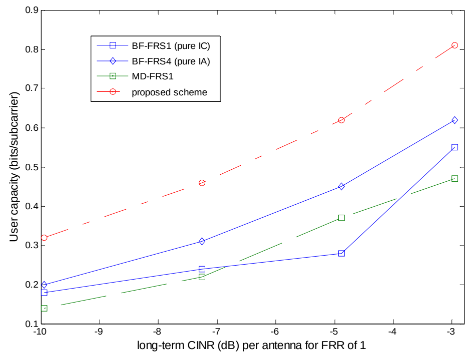
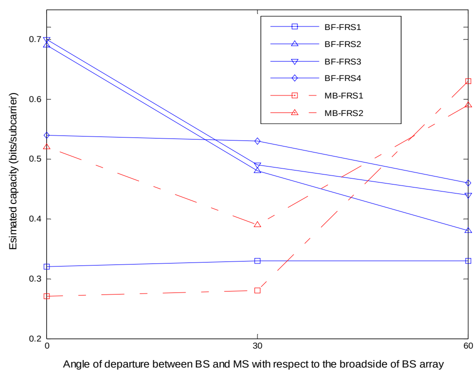


(a) Estimated capacity

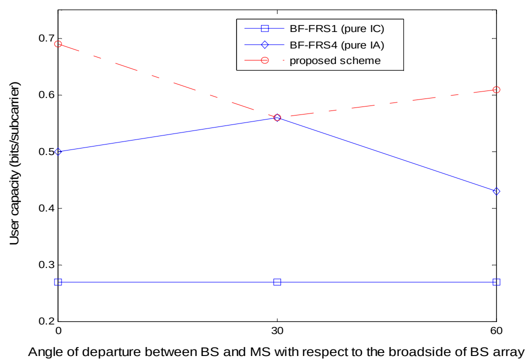


(b) User capacity

Fig.2. Capacity in the boundary between sector 0 and 1.



(a) Estimated capacity



(b) User capacity

Fig. 3. Capacity in the cell boundary region with an average CINR of -5dB.