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Performance Analysis of a CDMA Network with Fixed Overlapping Sectors in Nonuniform Angular Traffic

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***Abstract*— The problem of base station antenna assignment (BSAA) with minimum mobile transmit power (MTP) is studied for CDMA networks with fixed overlapping sector antenna architecture (FOSAA) where more than one co-located antenna is used to cover any space in the network. It is first noted that the non-FOSAA has limitations in switching users between in-cell sectors and also out-of-cell sectors in moderately-loaded networks. It is then shown that by employing overlapping sectors in FOSAA, we can exploit the flexibility of assigning a user to one of possibly many potential antenna to effectively support the nonuniform azimuthal traffic. It is also shown that the BSAA problem with minimum MTP is a special case of a general problem that was solved by Hanly and Yates. The process of dynamic cell sectoring is differentiated twofold as cell-breathing (CB) and cell-slicing (CS) and the latter can be viewed as being azimuthal discrete counterpart of the former radial scheme. The hybrid scheme, CB+CS, offers better performance in terms of minimum total MTP in a FOSAA system. Simulation results demonstrate the flexibility and effectiveness of the FOSAA system in nonuniform angular traffic.**

***Index Terms*— CDMA networks, fixed antenna, overlapping sector, performance analysis, base station assignment, nonuniform angular traffic, hot-sector.**

I. INTRODUCTION

THE effective use of spatial division multiplexing access (SDMA) techniques with code division multiplexing access (CDMA) technology has been well established [1], [2]. Traditionally, signals from different antenna are directed towards different sectors avoiding co-channel interference. In fixed overlapping sector antenna architecture (FOSAA) [3–5], the overlapping of sectors, where more than one co-located antenna can cover any space in a cell, is allowed in a controlled way. This overlapping poses some problems: in an orthogonal CDMA system, it becomes the code-assignment problem [3] where more than one code can be used simultaneously in a space and in non-orthogonal CDMA system, it becomes a signal-to-interference (SIR) control problem [5] where mobile transmit power (MTP) and base station antenna assignment (BSAA) have to be intelligently managed to control the mutual interference. In this paper, the latter problem is addressed specifically in hot-spot sector scenario.

Many techniques have been proposed in frequency division multiplexing access (FDMA) and time division multiplexing access (TDMA) systems to handle the hot-spot problem [6] including cell-splitting, cell-sectoring and channel borrowing. The above methods are mainly related to re-assigning the channel around the hot-spot area. However, in CDMA cellular networks, all of the cells/sectors can operate with the same channel without channel planning but with proper power control. Previous work on nonuniform traffic either in TDMA or FDMA [6], [7] or in CDMA [8], [9] dealt with the imbalance of load levels among cells, not sectors. However, in [10], limited amount of overlapping between adjacent sectors in a 3-cell system was considered to adaptively handle the traffic variations for non-CDMA systems.

In [11], [12], nonuniform distribution of mobiles within a cell was considered and adaptive sectoring (without using overlapping sectors) was used to somewhat alleviate the hot-spot problem in sectors for CDMA systems. There has been some work, for example in [13], where overlapping due imperfect sectoring is analyzed to quantify the performance degradation in CDMA systems; however, the adaptive sectoring with the use of multiple co-located sectors was not considered. To our knowledge, there is no published work in the literature that considers fixed fully overlapping sectors in a cellular CDMA system and analyzes the reverse link performance under non-uniform traffic with the angle of arrival. A recent paper [14] alluded the advantage of using overlapping sectors to handle the non-uniform traffic in CDMA systems.

The antenna array with adaptive beam forming has been effective in suppressing co-channel interference by setting nulls to interferers. Though smart antenna array system [2]

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can handle the azimuthal (or angular) load variations very effectively, its cost and complexity are of great concerns for implementation. In [15], the capacity improvement with the base station antenna array in CDMA systems is analyzed. One alternative to the adaptive antenna array system is to use switched multi-beam antenna system in which several narrow beams are used to spatially cover a cell. A beam receiving the desired signal with the highest signal strength is selected. In [16], a switched multi-beam antenna system where beam selection is done frame-by-frame basis is analyzed. In our work, we employ fixed overlapping beams because of the low complexity and the possible evolution from the current fixed sector system.

We differentiate the process of dynamic cell sectoring in FOSAA twofold as cell-breathing (CB) and cell-sectoring (CS) which can be viewed as to occur based on radial and azimuthal loads respectively. In a system with high interference variation with angle of arrival, we show that cell-breathing alone is not effective; hence, we propose to employ fixed overlapping sectors to control the interference azimuthally - which we call cell-slicing. We consider overlapping sectors as a means to implement azimuthal counterpart of the radial CB scheme in wideband CDMA systems exploiting the spatial characteristics of different mobile users. The performance of various base station antenna assignment (BSAA) schemes are evaluated via simulation in hot-spot sector environment with different degree of congestion levels. It is shown that CS scheme can improve the SIR performance in the face of nonuniform azimuthal loads. As expected, the hybrid scheme, CB+CS, outperforms all the other exploiting breathing and slicing techniques, in minimizing the total mobile transmit power (MTP) in the system.

High temporal variation of interference power exists in integrated multi-media wireless networks due to the bursty nature of the sources. Furthermore, in such systems the co-existence of high and low rate/low bit-error-rate (BER) users contributes to higher signal variation at the base stations with angle of arrival [17]. Hence, in the future wireless systems, higher spatial (both radially and azimuthally) and temporal interference variations can be expected. A scheme that can support any spatial interference variation is of great interest. We show that the hybrid scheme that employs FOSAA with the BSAA+PA algorithm can offer such an advantage.

The main contributions in this article can be summarized as follows. We (i) studied for the first time the combined problem of base station antenna assignment with minimum mobile transmit power (BSAA+MTP) for reverse links of a CDMA/FOSAA system, (ii) showed that the above BSAA+MTP problem is a special case of a general optimization problem solved by Hanly and Yates, (iii) proposed a pilot-power based iterative algorithm to implement the BSAA+MTP algorithm in FOSAA system for adaptive sectoring in angular and radial direction and (iv) showed through simulation studies that the FOSAA system can effectively and flexibly handle non-uniform angular traffic compared to the traditional non-overlapping sectored system.

The rest of this paper is organized as follows: The FOSAA is described in the next section. Then in Section III, FOSAA is analyzed for the reverse link and it is shown that there exists an optimal solution in minimum transmit power and that can be achieved using BSAA+PA algorithm. In Section IV, spatial interference filtering is discussed and then the exploitation of overlapping sectors to handle nonuniform azimuthal loads is studied. Simulation process is described in Section V. Then, the simulation results and analysis are given in Section VI. There, performance measures such as cumulative distribution function statistics of received SIR and total mobile transmit power are presented. Some practical issue in the implementation of FOSAA system is also described there. Finally, Section VII concludes the paper.

II. Fixed Overlapping Sector Antenna Architecture

Recently, a novel overlapping sector antenna architecture for wireless cellular systems was proposed in [5]. In this paper, its SIR performance and its ability to handle nonuniform azimuthal loads are investigated. In reverse links we assume complete non-orthogonal CDMA systems, which is the worst case, due to asynchronous nature of the transmission combined with multipath fading radio channels. In such a system, multiple antenna are used at the base station, each covering a sector. In the traditional cellular system with sectors such as IS-95, a cell is divided into 3 or 6 sectors, each being non-overlapping except for limited amount of overlapping especially around cell boundaries to implement soft handoff. There, fixed and directional antenna are used to suppress co-channel interference. In such a system, there is a limited flexibility in assigning users to different sectors of the *same* cell because of the limited antenna gain outside the main coverage area as discussed in [18]. As a result, this traditional sectored cellular architecture lacks the capability of supporting the nonuniform azimuthal loads.

In FOSAA [3], [5], the radiation patterns of antenna are arranged in a way that a user anywhere in a cell can communicate to more than one antenna with equally strong radio path[1]. This is achieved by having a set of co-located fixed and directional antenna whose coverage overlap spatially. Since each user has a freedom to select one of many antenna with equal radio path, we have more than one choice in the assignment of users to antenna which can be done based on the azimuthal load levels as discussed in Section VI.

Let the total number of antennas at a base station be K. Each antenna generates a radiation pattern that can azimuthally cover the angle of θ. Note that in general, antenna with different widths can be employed depending on the traffic conditions. We assume that these antenna are uniformly distributed. Let the number of overlapping antenna covering any point in the system be L - which is also referred to as *degree of overlapping*. Hence, it can be seen that,

$$L = \frac{K}{S} = \begin{cases} 1, & \text{if non-FOSAA,} \\ 2, 3, ... & \text{if FOSAA,} \end{cases} \tag{1}$$

[1]Since antenna are co-located the slow fading and distance-dependent loss are equal from a mobile to a set of (L) co-located antenna in a system that implements FOSAA. Home base station antenna is selected based on the above channel conditions (after averaging out the fast multipath fading). Hence, it is concluded that all L antenna are equally available for a mobile to select for operation.

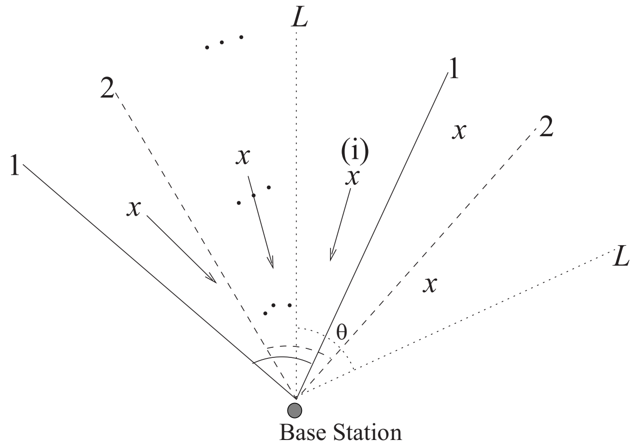

Fig. 1. Mobile i can potentially be covered by L antenna in FOSAA. Antenna "1" receives signals from users who may possibly be in communication with L different (co-located) antenna.

where $S = \frac{2\pi}{\theta}$, and S is the number of sectors in a cell as in the conventional (non-FOSAA) system. Fig 1 shows $L(> 1)$ antenna covering a user i and antenna "1" receiving signals from users who are in communication with possibly L different antenna in a FOSAA. Note that $0 < L \leq K$ and $L = \frac{K\theta}{2\pi}$ in our system model. Hence, we denote the FOSAA as $[K, L]$ in this paper.

It can be argued that instead of using K overlapping sectors with angular width of θ and L degree of overlapping in a cell, one can use K non-overlapping sectors with angular width of θ/L and get the similar or better performance. For example, 6 overlapping sectors with angular width of 120^o vs 6 non-overlapping sectors with angular width of 60^o. However, the following argument supports the use of overlapping sectors: (a) adaptive sectoring is needed to handle time-varying traffic intensity around the base stations, (b) the use of overlapping sectors (combined with dynamic intelligent code management) increases the downlink orthogonal code re-use efficiency as shown in [3], (c) there will be a practical limit on the minimum size of any sector and hence the use of overlapping sectors with relatively larger angular width may be desirable.

III. Optimal Mobile Transmit Power in FOSAA Systems

We consider the reverse link whose service quality is characterized by E_b/I_o. A user i requires E_b/I_o of γ_i^{req} and provide data rate of R_i for transmission. Transmitter activity factor of unity is assumed for all the users. Each user is equipped with only one omni-directional antennae. However, a base station uses several antenna that overlap in coverage to serve a cell as discussed in Section II. Neither soft handoff nor mobility is considered in our study. Total spreading bandwidth available is W MHz.

A set of N transmitters shares the same CDMA channel in the reverse link. The network consists of B base stations and FOSAA $[K, L]$ is implemented at each[2] base station. That is, K antenna are mounted at each base station with L degree of overlapping. Therefore, the total number of antennas used in the system is KB. Hence theoretically, a user can communicate with KB antenna, though practically with a small subset of them. The link gain between transmitter $i \in \{1, ..., N\}$ and receiver $j \in \{1, ..., KB\}$ is denoted by G_{ij} and the MTP by $P_i \geq 0$.

Let $a(i)$ be the home base station antenna of user i, i.e., transmitter i communicates with the receiver at $a(i)$. Let $\mathbf{U}(a(i))$ and $\overline{\mathbf{U}}(a(i))$ be a set of users who are inside and outside of the sector covered by $a(i)$ respectively. From $\mathbf{U}(a(i))$, let $\mathbf{H}(a(i))$ be a set of users (not including user i) whose home base station antenna is $a(i)$ and the rest, $\overline{\mathbf{H}}(a(i))$, is communicating with other antenna co-located with $a(i)$. Hence, $\overline{\mathbf{H}}(a(i)) = \{\mathbf{U}(a(i)) - \mathbf{H}(a(i)) - i\}$, that is $\overline{\mathbf{H}}(a(i))$ refers to users in the overlapping portion of the sector but belonging to the co-located antenna. Therefore, antenna $a(i)$ will be receiving signal from i and interference from $\mathbf{H}(a(i))$, $\overline{\mathbf{H}}(a(i))$ and $\overline{\mathbf{U}}(a(i))$. The desired signal for user i at receiver $a(i)$ is equal to $G_{ia(i)}P_i$, while the interfering signal power from other users is given in (2) (shown at the top of the next page) where the first, second and third terms come from intra-sector, inter-sector and intercell interference respectively. It can be seen that 2nd term in (2) is generally negligible in traditional non-FOSAA system. However in FOSAA system, this term can be substantial and play a major role in the assignment of users to antenna based on the azimuthal loads.

Eq. (2) can be written in general as,

$$I_j = \sum_{k \neq i} G_{kj} P_k, \qquad i = 1, ..., N \text{ and } j = 1, ..., KB. \quad (3)$$

Therefore, the received E_b/I_o for user i is can be written as,

$$\gamma_i = \frac{W}{R_i} \frac{G_{ia(i)} P_i}{I_{a(i)}}, \qquad i = 1, ..., N \text{ and } a(i) \in \{1, ..., KB\}. \quad (4)$$

From the system operation point of view, the goal is to minimize $\sum_i P_i$ subject to satisfying $\gamma_i \geq \gamma_i^{req}, \forall i$. The minimization occurs when $\gamma_i = \gamma_i^{req}, \forall i$ [19]. This is jointly done by finding the BSAA vector $\mathbf{A}$, and MTP vector $\mathbf{P}$, where $\mathbf{A} = [a(1), ..., a(N)]$ and $\mathbf{P} = [P_1 \quad ... \quad P_N]^{\mathrm{T}}$. Eq. (4) can be written in a matrix form as,

$$\mathbf{GP} = \mathbf{P}, \quad (5)$$

where $\mathbf{G}$ is the $N \times N$ normalized link gain matrix defined by,

$$\mathbf{G}_{ij} \equiv \begin{cases} 0, & i = j \\ \frac{R_i \gamma_i}{W} \frac{G_{ja(j)}}{G_{ia(i)}}, & i \neq j. \end{cases} \quad (6)$$

There are numerous papers that analyze the interference matrix $\mathbf{G}$ and the solution $\mathbf{P}$ (see [19], [20] and references therein) for non-FOSAA system. It can be seen here that $\mathbf{G}$ is non-negative, irreducible and stochastic. Hence, Perron-Frobenius [21] theory guarantees the existence of the solution in terms of transmit power if there exists a feasible solution.

By introducing additional antenna with overlapping coverage in FOSAA systems, we do not disturb the channel conditions but give additional flexibility to users to switch antenna since each user can communicate to more than one antenna with equally strong radio path. Hence, with the available antenna size of KB, the size of the possible BSAA vector

[2]Practically, FOSAA can be implemented in selected cells depending on the traffic conditions as we do in the simulation study.

$$I_{a(i)} = \sum_{k \in \mathbf{H}(a(i))} G_{ka(i)} P_k + \sum_{k \in \overline{\mathbf{H}}(a(i))} G_{ka(i)} P_k + \sum_{k \in \overline{\mathbf{U}}(a(i))} G_{ka(i)} P_k \qquad i = 1, ..., N, \tag{2}$$

is $(KB)^N$. Let l be one of the assignments and also $\mathbf{P}(l)$ and $\mathbf{G}(l)$ be the corresponding MTP vector and normalized interference matrix respectively. Hence, the MTP vector is said to be feasible under assignment l, if

$$\mathbf{P}(l) = \{\mathbf{P}(l) \geq 0 | \mathbf{P}(l) = \mathbf{G}(l)\mathbf{P}(l)\}. \tag{7}$$

Hanly [20] has solved the combined problem of selecting the base station antenna and finding the MTP in general form and proposed an iterative algorithm (see (6) and (7) in [20]). In this paper we use a variation of the above algorithm and is based on pilot-power control as given in [18]. There it was shown that if the forward link and the reverse link are reciprocal, both of these algorithms give the same optimal solution. We refer to this algorithm as *Base Station Antenna Assignment plus Power Adaptation (BSAA+PA)* algorithm in this paper. Hence, we use the BSAA+PA algorithm in finding the home antenna and adapting the transmit power to minimize the total MTP in the sequel.

IV. Spatial Interference Control and Cell Sectoring

We discuss four types of spatial interference filtering techniques using an example as shown in Fig. 2.

They are: (a) traditional 3-sector antenna with fixed BSAA (b) traditional sector(cell)-breathing, (c) 6 sectors with overlapping coverage plus no cell-breathing and (d) 6 sectors with overlapping coverage plus cell-breathing. The above schemes are respectively referred to as Fixed, cell-breathing[3] (CB), cell-slicing (CS) and cell-breathing plus cell-slicing (CB+CS) in this paper. In the first two, no FOSAA is assumed and in the last two, FOSAA is implemented. We include the Fixed and CS schemes just for the comparison purposes though in practice CB and CB+CS will be used.

In the rest of the paper, we replace the total interference I_j (in (3)) by the total received power Q_j, where $Q_j = \sum_k G_{kj} P_k$, and use it for simplicity. All the four techniques are implemented iteratively with n being the iteration index. Let us consider a case where sector B is overloaded (i.e., hot-spot sector) and sectors A and C are not, as shown in Fig. 2. In such a case, Fixed BSAA scheme does nothing but to block some users in sector B to avoid SIR degradation to already admitted users. In Fixed BSAA, users connect to the strongest (in radio distance sense) base station antenna and therefore in general,

$$a(i) = \arg \max_l \{G_{il}\}, \qquad \forall i, \qquad l = 1, ..., S \times B, \tag{8}$$

and the MTP is given as [22] as,

$$P_i(n+1) = \frac{\gamma_i R_i Q_{a(i)}(n)}{W G_{ia(i)}}, \qquad \forall i. \tag{9}$$

[3]Cell-breathing is a general term to describe the shrinking/expanding coverage of a cell (or sector) that can occur in either radial or azimuthal directions or both. However, in the literature it has been used to refer to only in radial direction and we too continue to do so.

The main problem with Fixed BSAA scheme is that the system accommodates mobiles in congested cells/sectors at the expense of higher transmit powers. By allowing the mobiles to switch base stations, we can reduce the total transmit power as done next in the dynamic BSAA.

We now allow mobiles to change their base station antenna dynamically based on radial, azimuthal and both radial/azimuthal load levels at the antenna in CB, CS and CB+CS respectively. As mentioned earlier, we use the BSAA+PA algorithm implemented using the pilot-power control [23] as discussed next.

At n^{th} iteration of the algorithm, base station antenna l transmits its pilot-power inversely proportional to its total measured power, $Q_l(n)$, at its receiver. For user i, the received pilot-power is,

$$\Lambda_{il}(n+1) = \frac{G'_{il}}{Q_l(n)},$$

where G'_{il} is the forward link gain between transmitter (antenna) l and receiver (mobile) i. It is assumed that forward and reverse links are reciprocal to implement pilot-power controlled BSAA. Mobiles sense the received pilot-power and pick up the strongest that determines the base station antenna. That is,

$$a(i) = \arg \max_l \{\Lambda_{il}\}, \qquad \forall i. \tag{10}$$

The MTP, $P_i(n)$ is given by (9). It should be noted that $a(i)$ is selected based not only on link gain but also with the congestion level consideration at the base station antenna receiver.

In CB, we can assign a mobile to one of (possibly) many antenna of the *adjacent* cells. In CS, with overlapping sectors, we can assign to one of (at least) L antenna of the *same* cell. In the hybrid CB+CS scheme, all possible antenna (in-cell and out-of-cell) are considered in the assignment for every mobile. In all of the dynamic BSAA schemes, we use the same algorithm; however, the difference lies in the pool of base station antenna that is available as candidates for a mobile.

A. Radial Control and Cell-Breathing (CB)

We assume that no FOSAA is implemented here. In CB, theoretically as well as practically, any mobile can connect to any antenna in the system, provided that there is a strong radio path between them. Using cell-breathing technique [20], some of the users in sector B can be arranged to be served by the adjacent light cells/sectors as shown in Fig. 2(b). Pilot power of sector B can be reduced shrinking the sector size (or load) and, hence making the users at the sector edge to link to other base stations. Here, the BSAA and the corresponding MTP are given by (10) with $l = 1, ..., S \times B$ and (9) respectively.

This technique *radially* limits the users, i.e, users above a certain radio distance from the base station can be controlled in terms of connectivity. Here, interference power was controlled by assigning a mobile to a lightly loaded (out-of-cell)

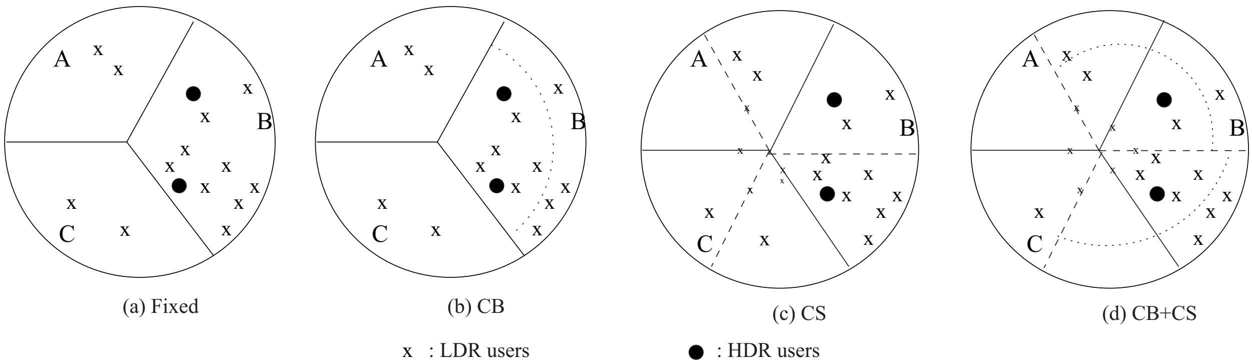

Fig. 2. Spatial interference control techniques. Low data rate (LDR) and high data rate (HDR) users co-exist in the system. In (c) and (d), dashed and solid lines denote the sectors of two different groups of non-overlapping sectors. Dotted lines denote the shrinking of the cell/sector size.

sector/cell. As shown in [18], this scheme has limitation in switching users between base stations in moderately-loaded networks.

B. Azimuthal Control and Cell-Slicing (CS)

In multi-media wireless systems, one high rate/BER user can cause a lot of interference to low rate/BER users [24]. If this high data rate user happens to be near the base station then cell-breathing technique would not help. However, with overlapping sectors, we have a choice of assigning this user to one of two adjacent (in-cell) sectors as shown in the Fig. 2(c). This assignment can be done depending on the azimuthal load conditions. Hence, this technique *azimuthally* limits the interference, making it more suitable for nonuniform interference with angle of arrival.

We implement FOSAA here; however, no mobile can connect to out-of-cell antenna (i.e., no CB). In practice, there will be no scheme that implements only CS scheme. However, for the comparison purposes, we consider CS scheme here. A mobile i can connect to one of the (in-cell) antenna whose coverage potentially include it. Here, a user i can connect to one of L (in-cell) antenna whose coverage potentially include it. The BSAA and the corresponding MTP are given by (10) with $l = 1, ..., L \times S$ and (9) respectively.

It can easily be proven that if a mobile is under the sector-coverage of L co-located antenna, it will always select an antenna whose total received power is minimum, provided that forward link gains between all L co-located antenna and the mobile are equal. Due to the overlapping, it is possible for mobiles to be handed off among co-located antenna based on azimuthal load levels. One can view as cells being sliced by the antenna in the coverage using this scheme (as seen in Fig. 3); hence, we call this technique *cell-slicing*. Though multiple antenna with overlapping coverage are installed at the base station, a subset of them will be activated at any time depending on the load conditions. This will be clear when simulation results are discussed later in Section VI.

C. Hybrid Control and Cell-Breathing plus Cell-Slicing (CB+CS)

The cell-breathing technique is appropriate for nonuniform radial load and the cell-slicing is appropriate for nonuniform azimuthal load. Hence, we propose a hybrid scheme employing both CB and CS (as shown in Fig. 2(d)) to be used in real traffic conditions.

Again, we implement FOSAA here. In practice, communication channel is initially established between a base station antennae and a mobile through pilot-power control. If mobiles are assigned based on pilot powers throughout the system, i.e., there will be no restriction on the base station antenna available for assignment; in which case, we will in fact be implementing both cell-breathing and cell-slicing. Hence, the antenna search space is increased L-fold in CB+CS case compared to CB scheme because of the additional antenna used in the overlapping coverage.

The algorithms that help select the BSAA vector $\mathbf{A}$, and the MTP vector $\mathbf{P}$ are given by (10) with $l = 1, ..., L \times S \times B$ and (9) respectively. It can be seen from the discussion in Section III that the CB+CS scheme allowing any user to connect to any antenna can achieve the optimal solution in minimum total MTP in FOSAA using BSAA+PA algorithm. In a way, FOSAA provides an avenue for Hanly's BSAA+PA algorithm to breathe radially (continuously) and azimuthally (discretely) further decreasing the total MTP.

V. Simulation Studies

It is believed that FOSAA will yield better performance in nonuniform azimuthal traffic; therefore, our investigation focuses on such a case where uniform and nonuniform mobile distribution are assumed in radial and azimuthal direction respectively. In particular, we focus our investigation into a particular cell with nonuniform azimuthal traffic in a CDMA network. As mentioned previously, FOSAA may need to be implemented in congested cells only. We consider such a congested cell in the simulation.

A. Simulation Setup

A network with 36 base stations is considered in our study. The base stations are located at integer points (l, m) where $l, m = 1, ..., 6$, as shown in Fig. 4.

Let the cell around $(4, 4)$ be denoted as *center cell*. This cell is covered with 3 non-overlapping sectors in non-FOSAA and 6 overlapping sectors in FOSAA. Fixed and CB schemes are implemented with non-FOSAA, and CS and CB+CS schemes are with FOSAA. A *hot-spot sector* is created inside the center

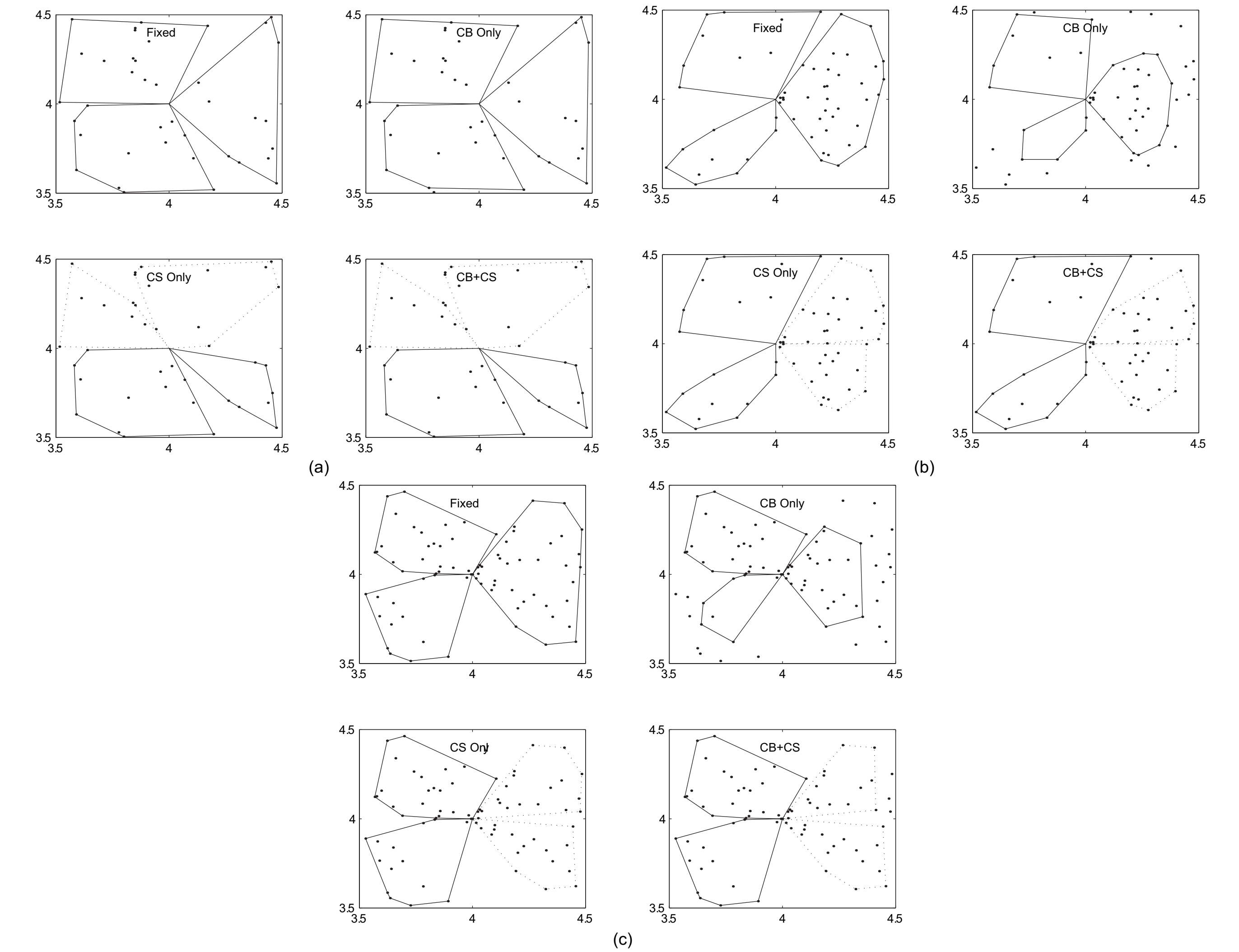

Fig. 3. Center cell coverage: (a) - with no hot-spot sector (uniform azimuthal traffic, $\beta = 0$). (b) - with one hot-spot sector (nonuniform azimuthal traffic, $\beta = 2$). (c) - with two hot-spot sectors (nonuniform azimuthal traffic, $\beta = 2$).

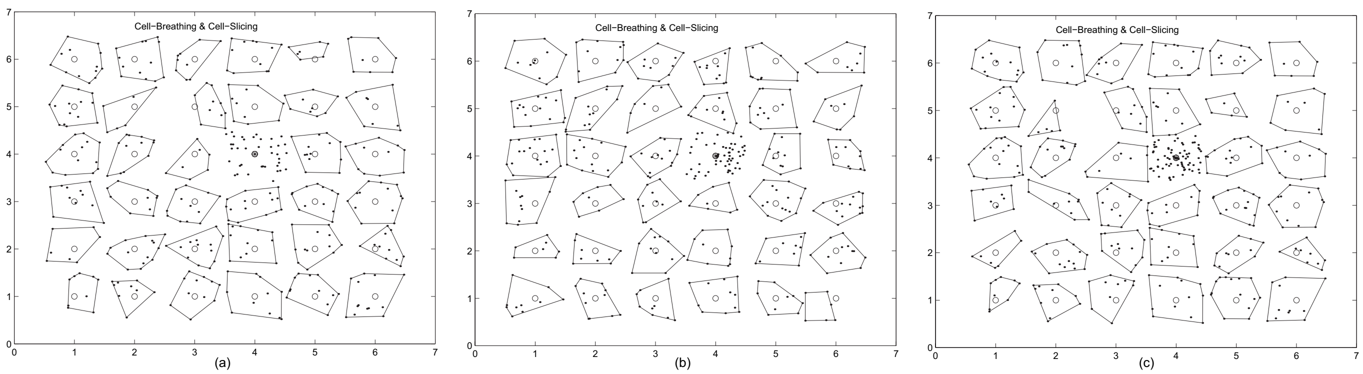

Fig. 4. Network coverage (for CB+CS): (a) with uniform azimuthal traffic, $\beta = 0$. No hot-spot sector is included. See Fig. 3 (a) for expanded center cell coverage. (b) with nonuniform azimuthal traffic, $\beta = 2$. A single hot-spot sector is included. See Fig. 3 (b) for expanded center cell coverage. (c) with nonuniform azimuthal traffic, $\beta = 2$. Two hot-spot sectors are included. See Fig. 3 [Right] for expanded center cell coverage.

cell as shown in Fig. 5(a). We implement a [6,2] FOSAA (i.e., 6 antenna with 2-degree of overlapping) only in the center cell.

The other cells are neither sectored nor overlapping. The above assumptions are not crucial to our investigation but simplify the simulation process.

First, we have taken 400 mobiles and distributed them randomly uniformly over the network which covers an area with coordinates (x, y) where $0.5 < x, y < 6.5$. Hence, the simulated network consists of a square area as shown in Fig. 4. Since only the center cell is covered with sector antenna, we further add 22 ($= \lfloor 2 \times \frac{400}{36} \rfloor$) mobiles randomly uniformly around the base station there. Therefore, the total number of mobiles in the center cell, before creating the hot-spot sector, is approximately 33 and they are evenly distributed among sectors. Finally, $11\beta, (\beta \geq 0)$ mobiles are added randomly uniformly in the hot-spot sector. Here, β can be regarded as a congestion control parameter for the hot-spot sector. Mobiles are symmetrically distributed about $\nu = 0^o$. It can be seen that $\beta = 0$ corresponds to a uniform mobile distribution in the center cell and $\beta = 1$ corresponds to a scenario where 50% of mobiles are in the hot-spot sector and the rest in the other two sectors of the center cell.

The radiation pattern of each antenna covers the entire sector with unity gain everywhere. The link gain is modelled as $G_{ij} = 1/d_{ij}^4$, where d_{ij} is the distance between mobile i and base station receiver j. 1. Our analysis and results are also valid for channels that undergo log-normal shadowing. However, in the simulation, we used only the distance-dependent path loss since the results obtained with it can intuitively be understood and easily verified. It is not difficult in the simulation to include the log-normal shadowing; however, we used the simple channel model to understand the fundamental behavior of the FOSAA systems.

We assume for simplicity, $R_i = 9.8$ kbps and $\gamma_i^{req} = 6.77$ dB, $\forall i$ with equal processing gain for all the mobiles; hence, using E_b/I_o and SIR interchangeably in the sequel. Though we assume homogeneous mobiles in the following, the results and analysis are equally applicable to the heterogeneous case.

We implemented the pilot power based BSAA+PA algorithm that was discussed in Section IV. When pilot power from a base station is reduced to control (i.e., shrink) the coverage area, there is a potential for coverage hole. In our implementation, transmit pilot power is inversely proportional to the load at the base station. A universal proportionality constant is used at all the base stations such that coverage holes are avoided. Each user selects the home base station by measuring the received pilot power and picking the base station with the largest received pilot power as its home base station. Unless all the received pilot powers are zero, each user will always find a base station, at least theoretically. By setting the proportionality constant to a higher value, we can guarantee a home base station for any user. Also, some degree of overlapping can be accommodated for practical purposes, e.g., to minimize the call dropping etc. by properly setting the proportionality constant.

Fig. 5(b) shows a hypothetical base station antenna assignment for mobiles in a cell that implements [6,2] FOSAA. As can be seen in Section VI-B.3, not all the antenna will be active at an instance. This is due to the relatively high inter-sector interference to some antenna. In CS and CB+CS, a set of antenna is selected for operation depending on the loading conditions in the cell using the algorithms discussed Section IV. In Fixed and CB schemes, all three antenna in the center cell are used.

We use the iterative algorithms discussed in Section IV in determining the home antenna for each mobile. For a certain set of mobile locations, the E_b/I_o's for all the mobiles in the network are computed and this process is repeated 20 times to account for the randomness in the location of the mobiles. As described later, for the case of nonuniform azimuthal loads, hot-spots are created 12 times to account for the randomness in the hot-spot location inside the center cell. Hence, a total of $10 \times 20 \times (422 + 11\beta)$ points are collected to plot the complementary cumulative distribution function (CDF) of received E_b/I_o.

B. Hot-spot Characteristics

Angular Width of Hot-spots: Angular width of the antenna beam (θ) can be made smaller to contain the signals of interest to a smaller area thus limiting the interference to others. The micro-manageablity of the hot-spots is increased with smaller beam width. Hence, hot-spots of different size (that is measured in relation to θ) or intensity can be effectively handled. The smaller the beam width is the more the capacity gain will be, if a large number of smaller sized hot-spots develops in a cell. On the other hand, smaller beam width necessitates larger number of antennas from coverage point of view, the complexity of managing the antenna beam increases and so does the softer handoff. In our simulation, θ is fixed at 120^o.

Random Locations of Hot-spots: Hot-spot can develop anywhere within a cell. In our simulation, the location of the hot-spots are randomized within a cell as follows: First, we generate high intensity of traffic in an area covered by a sector of width 120^o and obtain the results as described earlier. Then, a new hot-spot of angular width 120^o is selected by moving the center of the hot-spot by 30^o counter-clockwise. This procedure is repeated 12 times covering the entire cell. In the case of $\beta = 2$; a total of 106,560 data points are collected to generate the statistics. It should be noted that the orientation of the antenna is fixed during the above procedure.

VI. Performance Evaluation

The performance measures such as the total MTP, SIR and minimum number of antennas required are considered. We investigate three cases with no hot-spot sector, a single hot-spot sector and two hot-spot sectors in the simulation.

A. CB and CS Schemes with β

We first compare two schemes namely cell-breathing and cell-slicing in guaranteeing the required link quality as the congestion in a hot-spot sector varies. By changing the value of β, different amount of traffic is generated in a single hot-spot sector. It can be seen that CS scheme has the potential to effectively support nonuniform azimuthal loads than CB scheme.

Fig. 6 shows the complementary CDF of the received E_b/I_o for different values of β. It can be seen that as β increases, i.e., when congestion level increases in the hot-spot area, the difference in performance between CB and CS schemes becomes more apparent. For example, when $\beta = 1$, CB and CS schemes guarantee E_b/I_o of 6.85, 90% and 99% of the time respectively whereas, when $\beta = 2$, they do 65% and 96% of the time respectively as depicted in Fig. 6. This shows that cell-slicing can effectively support higher degree of nonuniform azimuthal load variation than cell-breathing.

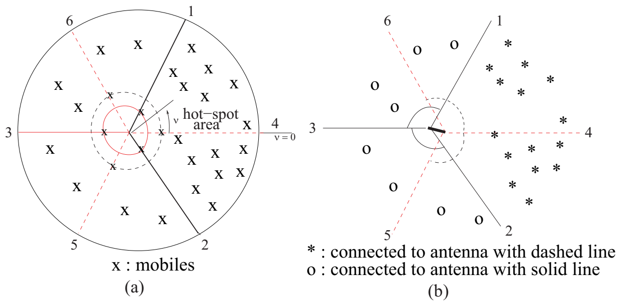

Fig. 5. An FOSAA [6,2] is implemented in a cell: (a) hot-spot area and (b) a hypothetical base station antenna assignment for mobiles.

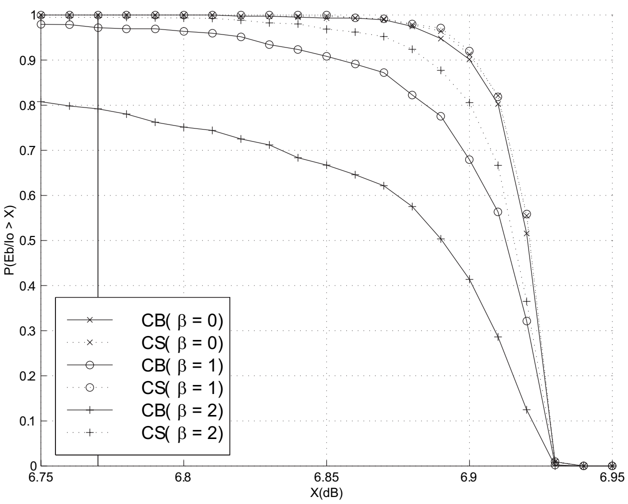

Fig. 6. Complementary CDF of E_b/I_o with sector congestion control parameter (β). A (randomized) single hot-spot sector is included.

B. All Four Schemes with A Single Hot-spot Sector in Uniform and Nonuniform Azimuthal Traffic

1) E_b/I_o Statistics: In all the schemes, after 10 iterations of the algorithms, the received E_b/I_o of all the mobiles were recorded. Two cases, $\beta = 0$ and $\beta = 2$ were considered, each respectively simulating the uniform and nonuniform azimuthal traffic around the base station at (4,4).

Uniform Azimuthal Traffic ($\beta = 0$): There are 422 mobiles in the network; with 3 times mobiles in the center cell as in any other cell. Sectoring is employed in the center cell. With the above feasible configuration of mobiles, the network was able to deliver the required quality of service to all the mobiles 99% of the time for all the cases including Fixed assignment. As expected, there was no noticeable gain in employing cell-breathing or cell-slicing, because of the fairly uniform mobile population and hence uniform interference powers with angle of arrival at the base stations. The network coverage is shown in Fig. 4 (Left).

Nonuniform Azimuthal Traffic ($\beta = 2$): The traffic in the hot-spot sector is increased from 11 to 33 corresponding to $\beta = 2$. Consequently, the received quality of service drops dramatically especially when employing Fixed assignment and cell-breathing cases as shown in Fig. 9.

Fixed assignment, CB, CS and CB+CS schemes provide the required quality of service, $50\%, 78\%, 98\%$ and 98% of the time respectively. With its inherent inability to handle hot-spots, Fixed assignment scheme suffers the worst while the hybrid scheme (CB+CS) performs the best. Most importantly, cell-slicing outperforms cell-breathing scheme by about 20% in delivering the required quality of service in this scenario. This clearly demonstrates the ability of the CS scheme over CB scheme in handling nonuniform azimuthal loads. Both CS and CB+CS perform comparatively since we do not exploit CB very much in our simulation; because, our focus is on nonuniform azimuthal loads and not on radial loads.

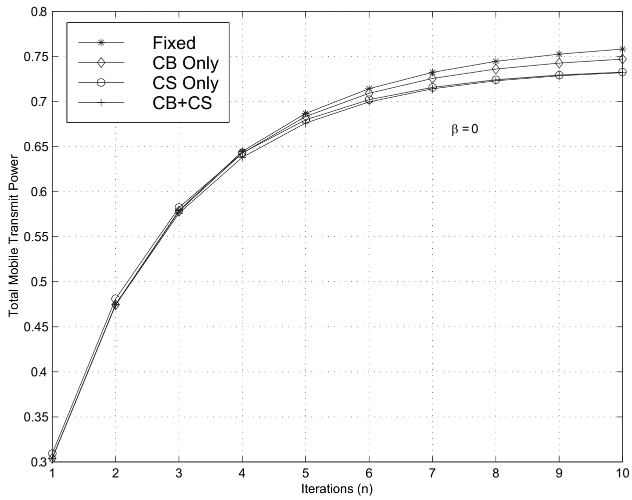

Fig. 7. Total Mobile Transmit Power in Uniform Azimuthal Traffic, $\beta = 0$.

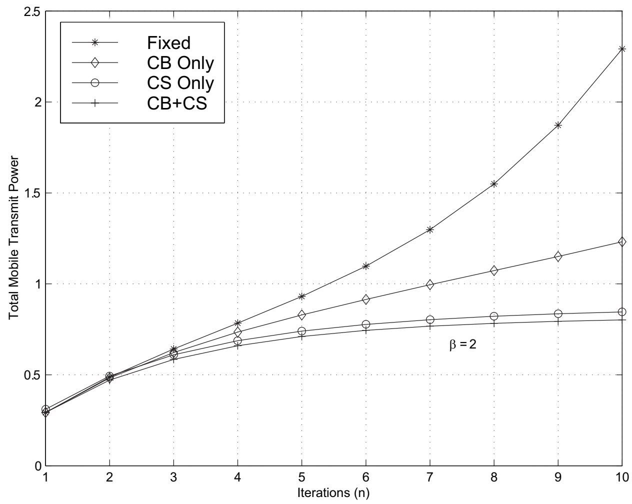

Fig. 8. Total Mobile Transmit Power in Nonuniform Azimuthal Traffic, $\beta = 2$.

We can see from Fig. 9 that if the system is required to provide guarantee on delivered E_b/I_o 99% of the time, CS and CB schemes will deliver 6.8 dB and 6 dB respectively. The gain in the E_b/I_o for CS scheme can be translated into capacity increase in CDMA systems. The network coverage is shown in Fig. 4 (Right).

2) Mobile Transmit Power: Figs. 7-8 show the required total mobile transmit power with the number of iterations for all four schemes for a set of mobile locations. Again, two cases, $\beta = 0$ and $\beta = 2$ are considered. As evident from the figures, CB+CS requires the smallest amount of power while Fixed assignment does the largest since the former is

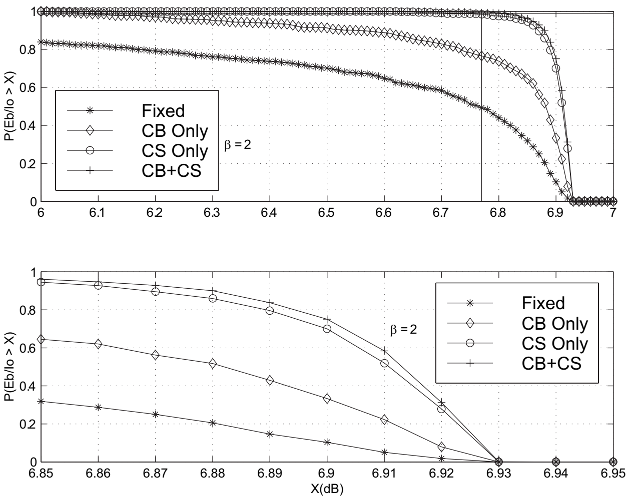

Fig. 9. Complementary CDF of received signal quality for all mobiles in nonuniform azimuthal traffic in the center cell, $\beta = 2$. A (randomized) single hot-spot sector is included.

the optimal solution. In uniform azimuthal traffic case ($\beta = 0$), no significant difference in mobile transmit power is noted as expected. With hot-spot sector scenario ($\beta = 2$), the Fixed assignment diverges (with no feasible solution) while others do converge.

The aforementioned cell-slicing algorithms (namely CS and CB+CS) select a set of antenna such a way to avoid those that are experiencing heavy interference (from users in the hot-spot area) as can be seen in Fig. 3 (Middle). By linking to the relatively lightly-loaded antenna of the same-cell (cell-slicing) and not linking to antenna of the other-cell (cell-breathing), mobiles operate and receive the required quality of service with lower transmit power.

3) Antenna Selection and Coverage: We now study how mobiles are assigned to base stations by looking at the coverage. When $L = 2$, the FOSAA [6,2] system can be seen to have two groups of non-overlapping antenna as depicted in Fig. 5(b), one denoted by solid line and the other by dotted line. It should be borne in mind that in Fig. 3, the adjacent-solid-line and dotted-line-antenna overlap.

Uniform Azimuthal Traffic ($\beta = 0$): Fig. 4(a) shows a snap shot of the mobile distribution in the network and antenna coverage of each base station antenna when implementing CB+CS scheme for $\beta = 0$. Since our focus is on the center cell, this cell is shown separately in Fig. 3(a). It is evident that there is no difference between implementing CB and not implementing it, in the case with uniform mobile distribution. Cell-slicing algorithm uses only four of the six antenna in serving the mobiles as shown in the bottom two graphs in the figure.

Nonuniform Azimuthal Traffic ($\beta = 2$): Fig. 4(b) shows a snap shot of the mobile distribution in the network and the antenna coverage for $\beta = 2$. Hot-spot cell is shown separately in Fig. 3(b) from which we can make the following observations: (1) the hot-spot cell shrinks radially in coverage when implementing cell-breathing (see top-right graph), (2) cell-breathing is not sought when cell-slicing can handle the scenario (see bottom-right graph), (3) with the overlapping coverage, the antenna that would potentially receive most of the interference power (e.g., in our case, that physically covers most of the hot-spot area) is not selected when implementing cell-slicing (see bottom two graphs) and (4) cell-slicing assigns mobiles to in-cell antenna without resorting to cell-breathing which would have assigned to out-of-cell antenna; as a result, would-be-handed-off (to out-of-cell) mobiles can be expected to use (cause) less power (interference) in cell-slicing than in cell-breathing.

Any antenna architecture should be able to handle the hot-spots regardless of its location. We looked at a snap-shot of the network, and if hot-spot develops in another area, different set of antenna will be selected for operation. Hence, this arrangement has the flexibility to adjust the BSAA assignment based on the loading conditions. Next, we compare the performance of the BSAA schemes when multiple hot-spot sectors develop in a cell.

C. All Four Schemes with Multiple Hot-spot Sectors

So far we assumed a single hot-spot sector. In general, there can be more than one hot-spot area at an instance within a cell. In this section, we study the performance of the BSAA schemes when multiple hot-spot sectors develop in a cell. In particular, we create two hot-spot sectors (with $\beta = 2$) in the center cell as follows: Two hot-spot sectors of width 120^o are created; one centered around $\nu = 0^o$ axis and the other by moving the axis of the hot-spot sector by 30^o counter-clockwise from previous location starting with $\nu = 0^o$. Hence, a total of 12 different double hot-spots are created. For a certain set of mobile locations, the E_b/I_o's for all the mobiles in the network are computed and this process is repeated 20 times giving a collection of 111,840 points to plot the complementary CDF of received E_b/I_o.

1) E_b/I_o Comparison: Fig. 10 shows the complementary CDF of E_b/I_o for all the users in the system for single (top graph) and double hot-spot sector (bottom graph) cases. Fixed, CB, CS and CB+CS schemes provide the required quality of service, $58\%, 70\%, 96\%$ and 98% of the time respectively with double hot-spot sectors; and $60\%, 79\%, 100\%$ and 100% of the time respectively with a single hot-spot sector.

Comparing with a single hot-spot sector case, the CDF plot is worse for double hot-spot sectors as expected since more users are added to the cell. However, CB+CS scheme outperforms CB scheme by about 28% in the latter case whereas the difference in the former case is about 21%. Therefore, we can conclude that the difference in performance between CB+CS and CB schemes becomes more significant with the increase in the number of hot-spot sectors. It should be noted that when we increase the number of hot-spot sectors from 2 to 3, we end up creating a uniform case in a 3-sector cell.

2) Total Mobile Transmit Power: The total MTP requirements for all the users are tabulated in Table I for different schemes. These results are reported following 10 iterations of the algorithms (i.e., upon convergence) averaged over 12 double hot-spot locations.

It is evident from the table that CB+CS scheme requires the least amount of power since it is optimal and the CB scheme

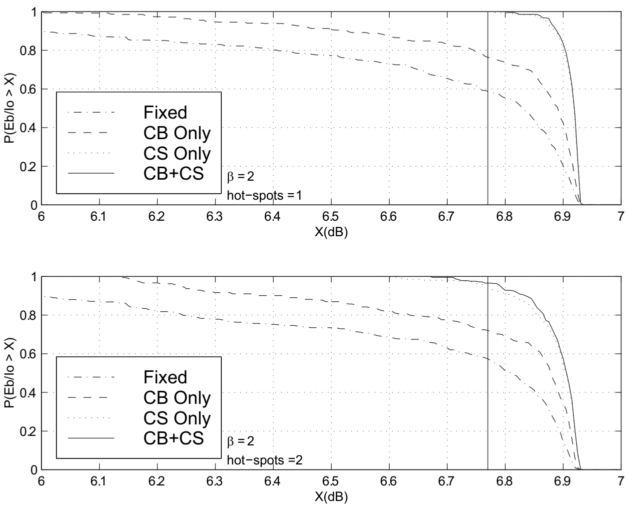

Fig. 10. Complementary CDF of received E_b/I_o for all users in nonuniform azimuthal traffic in the center cell, $\beta = 2$ with one hot-spot (top graph) two hot-spots (bottom graph).

	BSAA schemes			
	Fixed	CB	CS	CB+CS
Total MTP	37.42	23.38	18.72	18.04
Percentage	207%	130%	103%	100%

TABLE I

TOTAL MOBILE TRANSMIT POWER (MTP).

requires about 30% more power than in CB+CS scheme and as we have seen previously, CB+CS scheme provides the best guarantee in delivering the required link quality. Since we have fairly uniform radial loads in this simulation, both CS and CB+CS schemes perform comparably well. With the radial load fluctuations, we can expect to see the CB+CS outperforming the CS scheme.

3) Base Station Antenna Selection: Fig. 4 (Right) shows a snap shot of the mobile distribution in the network with two hot-spots in the center cell. The antenna selection and coverage in the center cell are shown separately in Fig. 3 (Right). The BSAA+PA algorithm selects the appropriate set of antenna in FOSAA depending on the loading conditions and minimizing the MTP. It can be seen that when employing FOSAA, a set of 4 antenna is selected in such a way to split the loads (and interference) in each of the hot-spot sectors.

D. Implementation Issues

1) Handoff: Handoff is one of the main concerns in wireless networks especially with highly mobile users and with high speed communications. By introducing additional antenna with overlapping coverage and selecting dynamically only a set of antenna, the number of handoffs will increase due to switching of users between antenna. If the received signal varies rapidly with the angle of arrival, then the set of selected antenna will also change increasing the number of handoffs. In our CDMA/FOSAA model, when an antenna is not used for communication, it will still be transmitting pilot power based on the received power. This will allow mobile users to switch to the best antenna when necessary. Therefore, when the received signals vary rapidly, this will cause ping-pong effect on the antenna choices for users. Since most of the handoffs will occur between sectors of the same base station (i.e., softer handoff) due to angular traffic, there will be no signaling overhead involved between base stations. Depending on the degree of traffic fluctuations, the number of handoffs will be large or small.

If the received signal quality at any antenna is greater than the threshold level when compared to the received signal quality at other antennas, then there is no need for handoff. However, in a wireless network that employs FOSAA, there is a greater potential for receiving high quality signals at one or more (co-located) antennas from a particular user. As a result, the softer handoff may be required. In our work, we have not studied the handoff problems and further investigation is necessary to understand the dynamics of handoff (both soft and softer) in FOSAA systems.

2) Deployment and Complexity Issues: In our work, reverse links are considered; and from the system point of view, one has to consider the forward links as well. Therefore, the cost of deploying the FOSAA system has to include also the forward link power. In order to evolve traditional sectored cellular architecture with overlapping architecture, more antennas and processing modules for each additional antenna are also required. We assumed ideal antenna patterns. As expected, if real antenna are used, the performance gain will be less than that with ideal antenna. Further studies are needed to quantify the performance gain in FOSAA systems with real antenna patterns. Details on how to design and fabricate a completely overlapping antenna with good sidelobe performance can be found in [25], [26].

VII. CONCLUSIONS

We investigated the fixed overlapping sectored antenna architecture as a potential means to handle nonuniform azimuthal traffic that can be very prevalent in multi-media wireless systems. We showed that the pilot-power based antenna assignment and power adaptation algorithm can naturally implement both cell-slicing and cell-breathing, hence controlling spatial interference effectively. The proposed architecture can smoothly be evolved from the current fixed non-overlapping antenna architecture. Simulation results clearly demonstrated the effectiveness and the flexibility of the FOSAA in handling nonuniform azimuthal loads. Though cell-slicing and cell-breathing plus cell-sling schemes performed comparatively well in our simulation, the latter hybrid scheme is expected to do better in the presence of nonuniform radial loads and in shadowing radio environment. These performance gains are realized at the expense of increased number of antenna, though only a subset will be active any time depending on the traffic conditions.

In the reverse link, potentially inherent antenna diversity gain can be exploited to improve the SIR. The correlation between the signal received at two different co-located antenna will determine the amount of improvement. The gain that can be achieved using adjacent sectors in FOSAA can be investigated. We assumed that total interference power at the base stations varies slowly so that the algorithm can handle the mobile assignment. Further study is needed to understand the dynamics of the mobile switching and activating/deactivating an antenna during the process of congestion control in FOSAA system.

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