On Mobility-Supporting Transmit Beamforming in MISO FDD Wireless Systems

Wookwon Lee and Brian J. Sepko

Abstract: **When operating in frequency-division duplex (FDD) mode, transmit beamforming in multiple-input single-output (MISO) wireless communication systems typically requires accurate knowledge of downlink channel state information (CSI) at the transmitter. In practical FDD systems, obtaining such downlink CSI at the transmitter is challenging, if not impractical. To circumvent such challenge and support user mobility, we present a new method for transmit beamforming based on simple beam-control commands (BCCs) in MISO FDD mobile systems. We then numerically evaluate the effects of BCC errors in terms of transmit power efficiency, system capacity, and outage probability.**

Index Terms: **Beam control command, frequency-division duplex, multiple-input single-output, transmit beamforming.**

I. INTRODUCTION

In transmit beamforming, particularly in multiple-input single-output (MISO) frequency-division duplex (FDD) systems, difficulties arise from various aspects different from receive beamforming [1]. At the center of such difficulties is the need for accurate channel state information (CSI) of the downlink at the base station. In typical transmit beamforming techniques (for instance, see [2–7]), the downlink CSI has to be *a priori* known, completely or partially. As linear transformations of the uplink channel knowledge at the base station are not suitable for transmit beamforming in FDD systems, the CSI is typically measured and/or estimated at mobiles and sent back through signaling to the base station on the uplink. In MISO FDD systems, unlike those in multiple-input multiple-output (MIMO) systems, mobiles are equipped only with a single antenna and thus have limited capability to explore spatial information of the downlink channel.

For facilitating transmit beamforming in MISO FDD systems, selective feedback or semi-blind suboptimal transmit beamforming could be used in conjunction with channel prediction [8], [9]. It is also shown that the transmit beamforming can still offer significant performance gain even with imperfect CSI [10]. However, all of these approaches do not essentially eliminate the need for CSI, and the accuracy of CSI estimation and sensitivity to estimation errors play a critical role in its overall performance. Furthermore, utilizing the CSI or its estimate for optimal or suboptimal transmit beamforming could easily become impractical, especially when mobiles are on the move and the CSI changes with time. Alternatively, if an antenna array is available for signal reception, as well as transmission, from the mobile to which the base station transmits with transmit beamforming, uplink direction-of-arrivals (DOAs) could be estimated and utilized such that transmit beamforming can be performed based on the look-directions [11], [12]. The accuracy of *absolute locations* of users is crucial in this approach, and multipath for the uplink could dramatically degrade the accuracy of DOA estimation and in turn affect the performance of transmit beamforming on the downlink.

In an effort to essentially circumvent the requirements of CSI and also of estimation accuracy in absolute locations of users, we consider transmit beamforming based on simple beam-control commands (BCCs). Since the mobile knows exactly what would be necessary for its quality-of-service (QoS) requirement, in the proposed method, each mobile generates a sequence of simple BCCs that are sent back to the base station for incremental changes in the transmit-beam pattern. The feedback mechanism is in a closed-loop fashion with one BCC at a time per beam-control period. As the proposed method is intended for MISO systems, each mobile is considered to have only a single antenna. As BCCs and CSI are somewhat different, this operation is equivalent to having transmit beamforming performed without any explicit knowledge of CSI.

While only a limited, independently performed work exists on the demonstration of functionality of a similar approach [13], the contributions of this paper are 1) to demonstrate the capability of the proposed method to fully support user mobility without CSI in MISO FDD systems and 2) to numerically evaluate the effects of BCC errors in terms of transmit power efficiency, system capacity, and outage probability. The rest of the paper is organized as follows. Section II provides a system model used in this paper, Section III describes the BCC-based transmit beamforming, and Section IV discusses the effects of BCC errors. Numerical results are provided in Section V and finally, concluding remarks are made in Section VI.

II. SYSTEM MODEL

Let us consider a MISO FDD base station equipped with a uniform linear array (ULA) of M isotropic antenna elements that serves K active mobile users equipped with a single antenna in line-of-sight (LOS) environment.[1] As the base station simultaneously communicates with all active mobiles, the instantaneous signal $\mathbf{x}(t) \in \mathbb{C}^M$ transmitted from the base station

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[1] We limit our discussion in this paper to a LOS scenario. Further work remains in non-LOS environment.

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beamformer can be expressed as

$$\mathbf{x}(t) = \sum_{j=0}^{K-1} \sqrt{P_j}\mathbf{w}_j s_j(t) \tag{1}$$

where P_j is the transmit power of the jth user signal $s_j(t)$ with $E\{|s_j(t)|^2\} = 1$ assumed, and the column vector $\mathbf{w}_j \in \mathbb{C}^M$ represents the beamforming weights for the jth user. Focused on the downlink between the base station and one mobile, for simplicity, we assume that user signals $\{s_j(t)\}$ are mutually orthogonal by an appropriate form of channelization, e.g., different frequencies in frequency-division multiple-access or signature codes in code-division multiple-access.

Then, with the commonly accepted far-field and narrow-band assumptions for the electromagnetic waves emitted from the base station antenna, the received baseband signal at mobile i can be written as

$$y_i = \sqrt{P_i} s_i(t)\mathbf{w}_i^T \mathbf{a}(\theta_i) + n_i(t) \tag{2}$$

where $n_i(t)$ is the additive white Gaussian noise (AWGN) with variance σ_i^2, and $\mathbf{a}(\theta_i) \in \mathbb{C}^{\mathrm{M}}$ is the channel column vector with its mth element given by $a_{mi} \triangleq c_{mi}\, e^{-j2\pi m d \sin(\theta_i)/\lambda_i}$, $m = 0, \cdots, M-1$, where c_{mi} is the complex path gain[2] from the mth antenna element of the base station to mobile i, d is the inter-element spacing of the ULA, θ_i is the angular location of mobile i in reference to the location of the base station, and λ_i is the wavelength of the carrier arrived at mobile i from the base station. The superscript $(\cdot)^T$ denotes the transpose. Note that $\mathbf{a}(\theta_i)$ is often referred to as the downlink CSI since it takes into account the complex path gain c_{mi} and mobile location θ_i and thus, represents the overall downlink propagation channel from the base station to mobile i.

III. TRANSMIT BEAMFORMING WITH SIMPLE BEAM CONTROL COMMANDS

A. BCC-based Operation

For illustration of the BCC-based operation, let us consider user mobility depicted in Fig. 1. Suppose the transmitted signal power at the base station is initially set to compensate the path loss and fading for mobile i at an angular location θ_i, i.e., point a. Then, we can draw a circle of radius r (solid line) to point a. The ith mobile is now moving with a speed of v towards an angular direction θ_v measured from the horizontal line perpendicular to the straight line connecting the mobile at point a and the origin of the polar coordinates, i.e., the location of the base station. The mobile finally arrives at point b. From (2), note that, for a given channel vector $\mathbf{a}(\theta_i)$, the quality of the received signal, e.g., signal-to-noise ratio (SNR) γ_i, is dependent on the transmitted signal power P_i and the beamforming coefficients $\mathbf{w}_i$. In the single-cell scenario, the transmit beamforming is performed such that the beamforming coefficients $\mathbf{w}_i$ are ultimately set to $\mathbf{a}^*(\theta_i)$, where $(\cdot)^*$ is the complex conjugate, and the signal power P_i is minimized for a given SNR threshold γ_{th}, which serves as a QoS measure.

[2]As transmit beamforming reduces reflections, diffraction, and scattering of electromagnetic waves often resulting in a smaller number of multipath components and less delay spread compared to omnidirectional transmission. Thus, for simplicity in this paper, a flat fading channel is assumed whose gain can be represented by a scalar parameter c_{mi}.

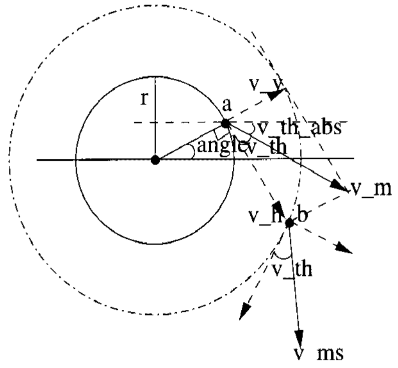

Fig. 1. User mobility diagram: Initial user location at an angular location of θ_i (i.e., point a) and a final location at point b.

In each beam-control period during the move, the mobile estimates its moving direction that could be either positive or negative horizontally, i.e., the direction of v_h, and generates a beam-control command. In the kth beam-control period, if the mobile knows its current location $\hat{\theta}_i^{(k)}$ or more specifically, its relative location to the direction of transmit beam pattern, it can certainly generate a *moving direction indicator* (MDI) by comparing the current location with the current record, $\hat{\theta}_{i,\text{mobile}}^{(k-1)}$, available at the mobile from the previous beam-control period such that

$$\mathrm{MDI}_i^{(k)} = \begin{cases} +1, & \text{if } |\Delta\hat{\theta}_i^{(k)}| > \Delta\varphi \text{ and } \Delta\hat{\theta}_i^{(k)} > 0, \\ -1, & \text{if } |\Delta\hat{\theta}_i^{(k)}| > \Delta\varphi \text{ and } \Delta\hat{\theta}_i^{(k)} < 0, \\ 0, & \text{else} \end{cases} \tag{3}$$

where $\Delta\hat{\theta}_i^{(k)} \triangleq \hat{\theta}_i^{(k)} - \hat{\theta}_{i,\text{mobile}}^{(k-1)}$ and $\Delta\varphi$ is an angular threshold. Generating beam-control commands is straightforward once MDIs are available. For instance, the BCCs to be delivered to the base station can be set to $\mathrm{BCC}_i^{(k)} = \mathrm{MDI}_i^{(k)}$, with $+1/-1$ for the positive/negative direction and 0 for no change.[3]

When the mobile moves towards an angular direction of θ_v, it may be gradually moving away from or coming close to the base station if $v_v \neq 0$. As the BCCs are intended to adjust the beamforming coefficients only, the transmitted signal power can be adjusted by integrating the conventional closed-loop power control as part of the overall operation with a step size Δp such that a preset threshold, i.e., γ_{th}, is jointly achieved for guaranteeing a QoS for the mobile. Table 1 summarizes the BCC-based method.

B. Rate of BCCs

To determine how often the update of beamforming coefficients should be, consider again the diagram in Fig. 1. The mobile's horizontal moving distance ξ_h during the time interval Δt is determined by $\xi_h = v\Delta t \cos\theta_v$, which can also be obtained by $r\Delta\varphi$ where $\Delta\varphi$ is the angular distance corresponding to Δt. If the main lobe of the transmit beam pattern is $\Delta\varphi$ radians wide and the directional gain is constant within the main lobe, then, the maximum time interval between two

[3]This BCC value of zero can be optional and may not be used if only one-bit representation of a BCC is desired.

Table 1. BCC-based transmit beamforming algorithm.

Step 1- *Initialization:* Set parameters for closed-loop power control such as step size Δp, rate μ_{PCC}, and SNR threshold γ_{th}, and for closed-loop beam control such as step size β and rate μ_{BCC}. Set the initial weight coefficients of the beamformer by an existing transmit beamforming method, e.g., [3].

Step 2- *BCC or PCC generation at mobile i:* For power control, if $\gamma_i^{(k-1)} < \gamma_{\text{th}}$, set $\text{PCC}_i^{(k)} = +1$ (up) and otherwise, $\text{PCC}_i^{(k)} = -1$ (down). For beam control, get $\hat{\theta}_i^{(k)}$ and set $\text{BCC}_i^{(k)}$ to $+1$, 0, or -1 based on (3). Update $\hat{\theta}_{i,\text{mobile}}^{(k)} = \hat{\theta}_{i,\text{mobile}}^{(k-1)} + (\text{BCC}_i^{(k)} \cdot \beta)$. Send $\text{PCC}_i^{(k)}$ or $\text{BCC}_i^{(k)}$ to the base station.

Step 3- *kth update at base station:* For the ith mobile, with $\text{BCC}_i^{(k)}$ or $\text{PCC}_i^{(k)}$, update the current mobile location by $\hat{\theta}_i^{(k)} = \hat{\theta}_i^{(k-1)} + (\text{BCC}_i^{(k)} \cdot \beta)$ or the transmit signal power by $P_i^{(k)} = P_i^{(k-1)} + (\text{PCC}_i^{(k)} \cdot \Delta p)$ dB, where P_i is initially normalized to 1. Then, update the mth element of the weight coefficients vector $\mathbf{w}_i^{(k)}$ for the ith mobile by

$$w_{i,m}^{(k)} = (\sqrt{P_i}/M)e^{j2\pi md\sin\hat{\theta}_i^{(k)}/\lambda_i}$$

for $m = 0, \cdots, M-1$

Step 4: Repeat Steps 2 and 3 for the entire duration of communication between the base station and the ith mobile, $i = 0, \cdots, K-1$.

consecutive updates that will allow successful tracking of the mobile location should be shorter than Δt. If the beam-control step size β is set such that $\beta = \Delta\varphi$, the BCC interval Δt_{BCC} is limited by $\Delta t_{\text{BCC}} < r\Delta\varphi / v\cos\theta_v$. From this, we can notice that, compared with the typical power-control rate μ_{PCC} of 800 bits per second (bps), the closed-loop beam control rate $\mu_{\text{BCC}} \triangleq 1/\Delta t_{\text{BCC}}$ can be much slower, while being able to track the mobile's horizontal mobility for beamforming purposes in most cells of a practical size.

For instance, if $\theta_i = 30^{\circ}$, $v = 60$ miles per hour (mph), $\theta_v = 10^{\circ}$, $r = 10$ mile, and $\Delta\varphi = 3.6^{\circ}$ (i.e., 0.06283 [rad]), the maximum BCC interval $\Delta t_{\text{BCC}} < 38.2$ sec, and if $r = 1$ mile, then, $\Delta t_{\text{BCC}} < 3.8$ sec. Certainly, the BCC step size β can be much smaller than $\Delta\varphi$ while maintaining $\mu_{\text{BCC}} \ll \mu_{\text{PCC}}$, which should not degrade the performance of power control when jointly employed with only one command, either PCC or BCC, sent back to the base station per PCC interval. The BCC rate can be flexibly increased to a higher rate if, for practical antenna arrays, the directional gains within the main lobe are not constant or a smaller beam-control step size is desired for the accuracy of beam direction. Note that the data rate on the uplink for BCCs should be substantially smaller, e.g., $\ll 800$ bps, than those of other existing optimal and suboptimal algorithms for MISO systems unless the required CSI for those algorithms could be represented in one or two bits per feedback interval, which is unrealistic.

C. Comments on Estimation of Moving Direction

For estimation of moving direction needed for the BCC-based transmit beamforming, one could possibly integrate a global positioning system (GPS) receiver for generation of BCCs and adjustment of direction-of-transmission (DoT), i.e., the direction of the main lobe, from the base station. However, as satellite signals for GPS are at the microwave bands, the GPS signals often degrade severely when obstacles exist or in buildings. In such cases, the mobile's *relative* location in reference to the DoT of the base station could be utilized [14] since the BCC-based operation needs MDIs rather than the absolute location information for generation of BCCs. Further study remains for more advanced algorithms for DoT estimation at the mobile equipped with a single antenna, as most existing methods for estimation of spatial parameters, e.g., see [15], are for the receivers equipped with an antenna array and may not be directly applicable.

D. Comments on Computational Complexity

For the proposed method, the computational complexity is at the mobile for estimation of mobile locations and generation of BCCs. It certainly depends on the estimation algorithm in place but, the estimation can be performed in one-dimensional search [14], the complexity of which should be acceptable in practical applications. Existing transmit beamforming techniques in MISO systems, however, require a higher level of computational complexity[4] in addition to the critical requirement on the downlink CSI. To illustrate this, let us consider the iterative optimal algorithms in [2] and [3]. In these algorithms, the computational complexity is at the base station and mainly comes from the fact that an M-dimensional brute-force search over all possible combinations of $\mathbf{w}$ is performed in each iteration for the optimal weight coefficients $\hat{\mathbf{w}}_i$. Other operations involved are for updating the transmitted power for the uplink and downlink, respectively, with the result from the aforementioned brute-force search although their computational complexity could be relatively negligible. As such, the overall complexity increases exponentially with the number of antenna elements M and linearly with the number of mobiles K.

IV. EFFECTS OF BCC ERRORS

The ultimate goal of transmit beamforming would be to optimize the directional gain for the transmitted signal $s_i(t)$ at the location of user i. From (2), the directional gain $G_{\text{BCC},i}$ for the ith signal $s_i(t)$ can be written as $G_{\text{BCC},i} \triangleq \mathbf{a}^T(\theta_i)\mathbf{w}_i$. In practice, the performance of the BCC-based transmit beamforming can be affected by several parameters such as the angular threshold $\Delta\varphi$, the accuracy of location estimation $\hat{\theta}_i$, the BCC step size β, and the BCC rate μ_{BCC}. But in this paper, in order to study the effect of BCC errors in a best-achievable scenario of transmit beamforming itself, we attribute the BCC error to the quality of location estimates and define it as the *percent error in the estimate of mobile location* $\hat{\theta}_i$, affecting the accuracy of

[4]In MIMO systems, this complexity could be substantially reduced by, for instance, the water-filling mechanism [16].

the directional beam for mobile i and its directional gain $G_{\text{BCC},i}$. For the measure of the effect of BCC errors, we primarily consider the source power efficiency of the transmitter, and then extend it to the service outage probability and the channel capacity.

A. Mathematical Modeling of BCC Errors

Let us consider a mobile user moving in one angular direction around the base station. The quality of the received signal is affected by the directional antenna gain and channel fading due to user's mobility. Suppose the average transmit power $\bar{P}_i \triangleq E\{|s_i(t)|^2\}$ is set to meet a certain QoS that is prescribed by the condition of $\bar{\gamma}_i \geq \gamma_{\text{th}}$ where $\bar{\gamma}_i$ is the average received SNR at mobile i and γ_{th} is the threshold. From (2), the instantaneous SNR can be written as

$$\gamma_i = P_i|\mathbf{a}^T(\theta_i)\mathbf{w}_i|^2/\sigma_i^2 = P_i|G_{\text{BCC},i}|^2/\sigma_i^2. \qquad (4)$$

With accurate estimates of the mobile location θ_i and complex path gain, the optimum beamforming for mobile i is achieved by setting the weights $\mathbf{w}_{i,\text{opt}} = \mathbf{a}^*(\theta_i)/\|\mathbf{a}(\theta_i)\|^2$ (normalized), and the SNR simply becomes $\gamma_i = P_i/\sigma_i^2$ as the normalized power gain $|G_{\text{BCC},1}|^2$ becomes unity. Without loss of generality, we assume that the ULA at the transmitter is placed along the y-axis of the x-y 2-dimensional plane while centered at the origin. Then, the mobile location θ_i can be modeled as a random variable and it is uniformly distributed over a range of angular locations in the right-hand side of the plane with the maximum range being $[-\pi/2, \pi/2]$. Furthermore, it is reasonable in practice to say that the mobile location θ_i and the complex path gain due to fading are statistically independent of each other. So, let us momentarily assume that the complex path gain c_{mi} embedded in $\mathbf{a}(\theta_i)$ is constant and further normalized to unity.

Now, with the BCC errors as defined above, suppose that the estimate of mobile location $\hat{\theta}_i$ is inaccurate and can be written as $\hat{\theta}_i = \theta_i + \epsilon$, where $\epsilon \in [0, 1]$ is the BCC error, such that the weight coefficients are determined by $\mathbf{w} = \mathbf{a}^*(\hat{\theta}_i)/\|\mathbf{a}(\hat{\theta}_i)\|^2$. Then, the instantaneous SNR becomes $\gamma_i = P_i|G_{\text{BCC},i}|^2/\sigma_i^2$ with $|G_{\text{BCC},i}|$ given by

$$\begin{aligned}|G_{\text{BCC},i}| &= \frac{|\sum_m \exp\{-j2\pi md[\sin\theta_i - \sin(\theta_i + \epsilon)]/\lambda_i\}|}{\|\mathbf{a}(\hat{\theta}_i)\|^2} \\ &= \sqrt{G_{x,i}^2 + G_{y,i}^2}/\|\mathbf{a}(\hat{\theta}_i)\|^2 \qquad (5)\end{aligned}$$

where, for notational simplicity, we have defined

$$G_{x,i} \triangleq \sum_m \cos[\alpha_m(\theta_i, \epsilon)], \qquad (6)$$

$$G_{y,i} \triangleq \sum_m \sin[\alpha_m(\theta_i, \epsilon)] \qquad (7)$$

with temporary random variables $\alpha_m(\theta_i, \epsilon) \triangleq 2\pi md\,[\sin\theta_i - \sin(\theta_i + \epsilon)]/\lambda_i$. The conditional probability density function (PDF) $f_{|G_{\text{BCC},i}|^2}(\xi|\,\epsilon)$ of the power gain $\xi = |G_{\text{BCC},i}|^2$ distributed over $[0, 1]$ would be of interest. This PDF could be obtained numerically if the PDF $f_{\theta_i}(\theta)$ of θ_i is known since $|G_{\text{BCC},i}|^2$ is essentially a function of θ_i as shown in (5). Fig. 2 shows examples of PDF $f_{|G_{\text{BCC},i}|^2}(\xi|\,\epsilon)$ for various values of ϵ. Each curve was numerically obtained from (5)–(7) with 50,000 samples of mobile location θ_i uniformly distributed over $[-2\pi/3, 2\pi/3]$.[5] As expected, for $\epsilon = 0$, the normalized power gain is always 1. But, for different BCC errors with $|\epsilon| > 0$, the shapes of PDF curves vary. This implies that a general closed-form analytical expression for $f_{|G_{\text{BCC},i}|^2}(\xi|\,\epsilon)$ may not be easily available although (6) and (7) may have a finite number of solutions for $\alpha_m(\theta_i, \epsilon)$ for the given distribution of mobile locations. Also, note that in Fig. 2, the curves for the same value of $|\epsilon|$ are not necessarily symmetric since the beam pattern for a ULA is not symmetric for both sides of the main lobe unless the main lobe is directed towards $\theta_i = 0$, and thus the effects of BCC errors differ. For illustration of the beam pattern, see Figs. 3 and 4 in Section V. In the next subsection, we briefly describe three measures adopted for numerical evaluation of the effect of BCC errors and present them in a format taking $G_{\text{BCC},i}$ into account.

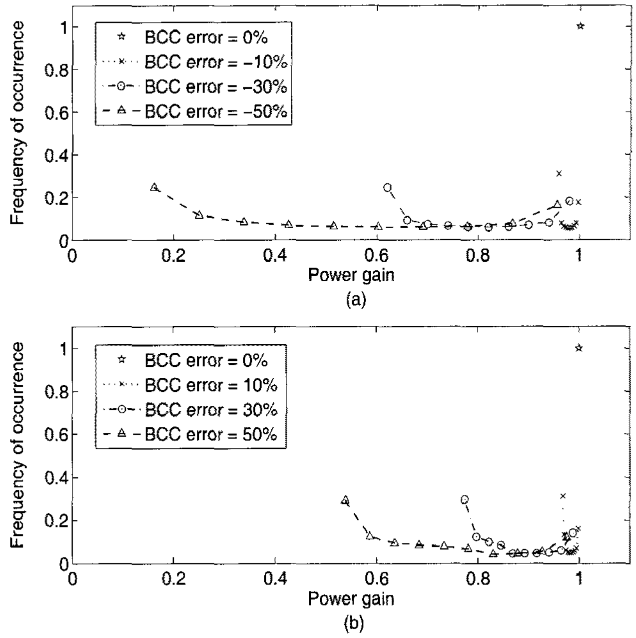

Fig. 2. Probability density function $f_{|G_{\text{BCC},i}|^2}(\xi|\epsilon)$ for (a) BCC error $\epsilon < 0$ and (b) $\epsilon > 0$; $M = 4$, $d = \lambda_i/2$, and carrier frequency $f_c = 2$ GHz.

B. Measures for the Effect of BCC Errors

B.1 Efficiency of Transmit Source Power

The transmit power P_i of user signal $s_i(t)$ is, strictly speaking, the power radiated from the antenna if an omnidirectional antenna is used and directly related to the amount of antenna source power needed. On the other hand, for a directional antenna, given a maximum directional gain G at the main lobe, the term *effective isotropic radiated power* (EIRP) is commonly used in reference to the total power that would be radiated by a hypothetical single antenna with radiation intensity equal to the maximum radiation intensity of the antenna array and can be expressed as [1]

$$\text{EIRP} = qGP_s \qquad (8)$$

[5]For BCC errors of up to ±50% considered, this range of mobile locations is chosen since the ULA beam can be directed towards a maximum of $\pm\pi/2$.

where q is the *antenna reflection (or mismatch) efficiency* and P_s is the source power. Note that G in (8) is the actual power gain, as opposed to the normalized one mentioned in the previous section, and is the same value as the normalized power gain scaled by the number of antenna elements M. That is, $G = 1$ for an omnidirectional antenna and $G > 1$ for directional antennas. Thus, a general interpretation of (8) is that for a fixed amount of P_s, as the directional gain increases, the EIRP increases and thus the received signal quality is enhanced.

But, it also implies that for a certain level of EIRP that would guarantee a preset QoS, the source power could be saved as the gain G increases. Then, for the total radiated powers of an isotropic antenna and an M-element array, a source power efficiency ζ can be formulated and expressed as

$$\zeta \triangleq \frac{P_{s,\,\text{iso}} - P_{s,\,\text{array}}}{P_{s,\,\text{iso}}} = 1 - \frac{\text{EIRP}/qG}{\text{EIRP}/q} = 1 - \frac{1}{G}. \quad (9)$$

This equation essentially means that ζ (when expressed in per cent) of the antenna source power is saved in delivering the same signal power to the mobile in reference to the source power needed by a hypothetical omnidirectional antenna. When the power gain of an antenna array degrades due to BCC errors, the transmitter shall need to adjust its instantaneous transmit power for the ith mobile inversely proportional to $M|G_{\text{BCC},i}|^2$ in order to compensate the effect of BCC errors for a given QoS. Thus, corresponding changes in ζ can be obtained by replacing G in (9) with $M\overline{|G_{\text{BCC},i}|^2}$ where $\overline{|G_{\text{BCC},i}|^2} \triangleq E_{\theta_i}\{|G_{\text{BCC},i}|^2|\ \epsilon\}$.

B.2 Service Outage Probability

The service outage probability can be defined in various ways but is essentially an indicator of how often the wireless link's quality falls below a specified acceptance level. As in the previous section, when the SNR is used as a QoS parameter, for a target SNR γ_{th} and an average received SNR $\bar{\gamma}_i$ at the mobile receiver, the service outage probability can be defined by [17]

$$P_{\text{out}}(\gamma_{\text{th}}, \gamma_i^{(\text{tx})}) \triangleq \text{Prob}\{\bar{\gamma}_i < \gamma_{\text{th}}\} \quad (10)$$

where $\gamma_i^{(\text{tx})} \triangleq \bar{P}_i/\sigma_i^2$ is referred to as the average transmit SNR and $\bar{\gamma}_i = \gamma_i^{(\text{tx})}$ for the system considered in this paper. For quasi-static channels where the channel is changing slowly with respect to the length of a data packet, the service outage probability for transmit antenna arrays with a small number of elements, e.g., $M = 1, 2$, and 3, can be succinctly written as [18]

$$P_{\text{out}}(\omega) = \begin{cases} 1 - e^{-\omega}, & M = 1, \\ 1 - e^{-\omega}(1+\omega), & M = 2, \\ 1 - \frac{1}{2}e^{-\omega}(2 + 2\omega + \omega^2), & M = 3 \end{cases} \quad (11)$$

where $\omega \triangleq \gamma_{\text{th}}/\gamma_i^{(\text{tx})}$.

As the effect of BCC errors in the transmit beamforming is translated into the reduction of the directional gain, equivalent to a reduction of the transmit SNR, the service outage probability in the presence of BCC errors can be evaluated by scaling the average transmit SNR $\gamma_i^{(\text{tx})}$ by a factor of $\overline{|G_{\text{BCC},i}|^2}$ such that $\hat{\omega} = \gamma_{\text{th}}/(\gamma_i^{(\text{tx})}\overline{|G_{\text{BCC},i}|^2})$ replaces ω in (11).

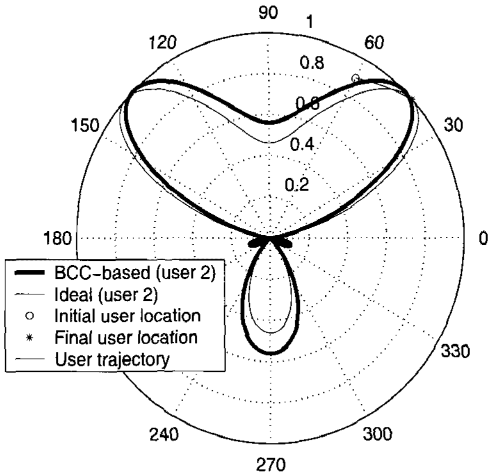

Fig. 3. BCC-based beamforming for a single user: Initial location at $\theta_{i,\text{initial}} = 60^\circ$, final location at $\theta_{i,\text{final}} = 42.3^\circ$, $v = 25$ mph, and $\theta_v = 20^\circ$.

B.3 Downlink Channel Capacity

There are various factors affecting the capacity of a radio link. One of such factors is the constraint on the average transmit power $\bar{P}_i$ for mobile i. With BCCs in error, the average transmit power is affected by a factor of $\overline{|G_{\text{BCC},i}|^2}$ and the effective average transmit power becomes $\bar{P}_{\text{BCC},i} = \bar{P}_i \cdot \overline{|G_{\text{BCC},i}|^2}$. For MISO systems in a fading channel, the channel capacity C with perfect knowledge of the channel can be written as [8]

$$C = \sup_{P(\mathbf{a}) \in \mathcal{P}} E_{\mathbf{a}}[C(P(\mathbf{a}))] = B\int_{A_0}^{\infty} \log\left(\frac{\|\mathbf{a}\|^2}{A_0}\right) f_{\mathbf{a}}(A)dA \quad (12)$$

where $\mathbf{a}$ is used in place of the channel vector $\mathbf{a}(\theta_i)$ for notational simplicity, $C(P(\mathbf{a}))$ is the instantaneous channel capacity defined over the signal bandwidth B, $f_{\mathbf{a}}(A)$ is the PDF of the random variable $A \triangleq \|\mathbf{a}\|^2$, $\mathcal{P}$ is a set of transmit-power values, $\{P(\mathbf{a})\}$, satisfying the constraint on $\bar{P}_{\text{BCC},i}$, i.e., $\int P(\mathbf{a}) f_{\mathbf{a}}(A)dA \leq \bar{P}_{\text{BCC},i}$, and $A_0 > 0$ is numerically obtained from

$$\int_{A_0}^{\infty} \left(\frac{1}{A_0} - \frac{1}{A}\right) f_{\mathbf{a}}(A)dA = \frac{\bar{P}_{\text{BCC},i}}{\sigma_i^2}. \quad (13)$$

Note that when each path gain c_{mi} is modeled as a complex-valued independent Gaussian random variable with zero-mean and variance σ_c^2 and thus the amplitude gain $|c_{mi}|$ is of Rayleigh distribution, the PDF of the total power gain A of the MISO channel becomes a Chi-squared distribution with $2M$ degrees of freedom and is written as

$$f_{\mathbf{a}}(A) = \frac{1}{(2\sigma_c^2)^M \Gamma(M)} A^{M-1} e^{-A/2\sigma_c^2}. \quad (14)$$

Also, note that with each path's power gain set to 1, i.e., $|c_{mi}|^2 = 1$, the variance σ_c^2 is 1/2.

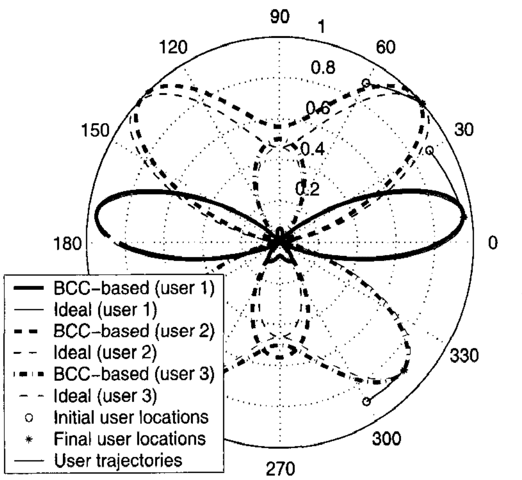

Fig. 4. BCC-based beamforming for three users: Initial locations at $\theta_{i,\text{initial}} = \{30^\circ, 60^\circ, -60^\circ\}$, final locations at $\theta_{i,\text{final}} = \{7.3^\circ, 42.3^\circ, -44.1^\circ\}$, $v = \{30, 25, 20\}$ mph, and $\theta_v = \{10^\circ, 20^\circ, 180^\circ\}$.

V. NUMERICAL RESULTS

In order to demonstrate the transmit beamforming towards mobile users, the operational performance of the proposed scheme is evaluated in computer simulation and compared with that of the optimum beamforming. To afford the computational complexity of optimum beamforming, we limit the number of antenna elements to 3 for both algorithms. Fig. 3 shows a beam pattern for a mobile at a final location after 40,000 BCCs. For this simulation, we have assumed the following parameters: $v = 25$ mph, $\theta_v = 20^\circ$, $\theta_i = 60^\circ$, $r = 10$ miles, $\Delta\varphi = 3.6^\circ$, $\Delta p = 1$ dB, $\mu_{\text{PCC}} = 800$ bps, and $\mu_{\text{BCC}} = 80$. We further assumed that the channel fading parameter c_{mi} is perfectly compensated at the mobile and the mobile's current location is accurately estimated in each beam-control period for the purpose of generating error-free BCCs. For AWGN, the SNR threshold γ_{th} is set to 22 dB. As shown in this figure, the BCC-based operation successfully tracks the mobile location and directs the transmit beam towards it. Fig. 4 shows another operation with three mobile users. We assumed the following parameters for three users: $v = \{30, 25, 20\}$ mph, $\theta_v = \{10^\circ, 20^\circ, 180^\circ\}$, and $\theta_i = \{30^\circ, 60^\circ, -60^\circ\}$. All other assumptions were the same as for Fig. 3. Note that as mentioned in Subsection IV-A, the beam pattern for each user is not symmetric in both sides of the main lobe. Furthermore, the beam widths are not the same for all users and depend on mobile location. This causes different effects of BCC errors in average power gain as shown next in Figs. 5 and 6.

The average power gain towards each mobile is of interest for observation as it directly impacts the amount of the source power required to guarantee a preset QoS for the mobile. With the presence of BCC errors, we numerically evaluated the conditional average power gain $\overline{|G_{\text{BCC},i}|^2}$ based on (5) with 50,000 samples of mobile locations for different numbers of antenna elements. Figs. 5 and 6 show the results for different ranges

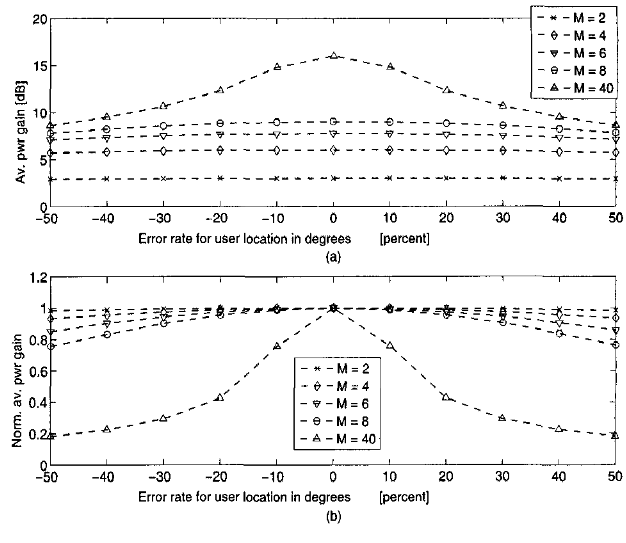

Fig. 5. Average power gain in the presence of BCC errors. Users are uniformly distributed between -15 to $+15$ degrees: (a) Actual $\overline{|G_{\text{BCC},i}|^2}$ in dB, (b) normalized $\overline{|G_{\text{BCC},i}|^2}$.

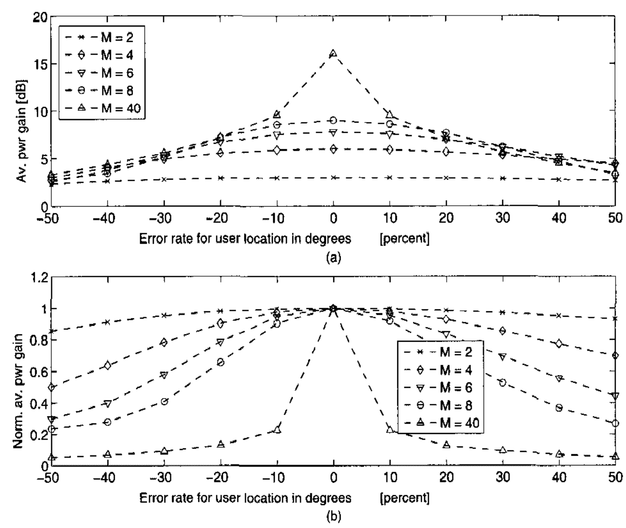

Fig. 6. Average power gain in the presence of BCC errors. Users are uniformly distributed between -60 to $+60$ degrees: (a) Actual $\overline{|G_{\text{BCC},i}|^2}$ in dB, (b) normalized $\overline{|G_{\text{BCC},i}|^2}$.

of uniformly distributed mobile locations. In each figure, part (a) shows actual and part (b) shows normalized average power gains. As expected, the directional gain degrades as the BCC error increases in both positive and negative directions. The degradation gets rapidly severe as the number of antenna elements increases since, with more antenna elements, the beam width is narrower and thus, mobile locations are more likely off of the main lobe with higher BCC errors. One interesting fact is that when mobiles are distributed in a relatively wider range, e.g., $[-60, +60]$ degrees compared to $[-15, +15]$ degrees, and BCC errors are higher, e.g., 50%, the actual average power gain of an antenna array with more elements becomes lower than that from a smaller number of antenna elements for the same BCC error as shown in Fig. 6(a). This results in a reduced source-power efficiency as will be shown below.

Next, we numerically calculate the transmit source power efficiency ζ from (9) based on actual average power gains in

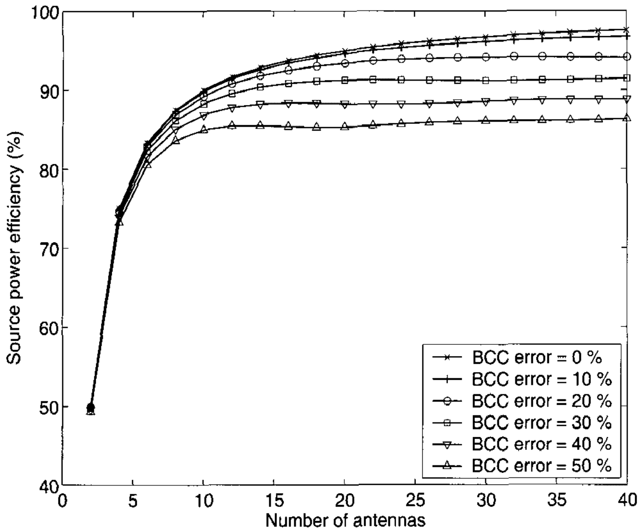

Fig. 7. Average source power efficiency ζ vs. number of antennas M in the presence of BCC errors ranging from 0 to 50%. Users are uniformly distributed between -15 to $+15$ degrees.

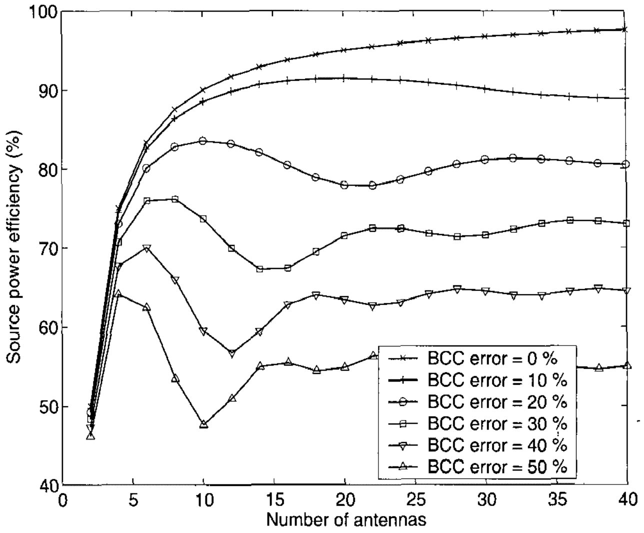

Fig. 8. Average source power efficiency ζ vs. number of antennas M in the presence of BCC errors ranging from 0 to 50%. Users are uniformly distributed between -60 to $+60$ degrees.

Figs. 5(a) and 6(a) and present them in Figs.7 and 8, respectively, as a function of the number of antenna elements for BCC errors ranging from 0 to 50%. As expected, the source power efficiency steadily increases with the number of antenna elements when no BCC errors exist. However, the efficiency decreases as the BCC error increases. Moreover, as anticipated from the data shown in Fig. 6(a) and as shown in Fig. 8, the source power efficiency for some larger numbers of antenna elements is lower than that for a smaller number of antenna elements when the BCC error is relatively high and mobiles are more widely distributed. In particular, from the curves for BCC errors of 20% $\sim$ 50% in Fig. 8, we observed that antenna arrays with a certain number of elements experience deep degradation in its efficiency, e.g., $M = 20$ for BCC error of 20%, $M = 15$ for 30%, $M = 12$ for 40%, and $M = 10$ for 50%. Also note that for a 4-element array with up to a certain BCC error, e.g., 40%, its power efficiency is greater than that of a smaller number of antenna elements, e.g., $M \leq 3$, with no BCC errors.

Fig. 9 shows the service outage probability P_{out} from (11) for the number of antenna elements ranging from 1 to 3. The data from Fig. 6(b) are used for the average power gain. We note that while BCC errors increase the outage probability in general, lower outage probabilities can still be achieved with an antenna array of $M = 3$, even with BCC errors, than those with $M < 3$. As shown in Fig. 10, similar observations can be made for the channel capacity C which was obtained from (12) in a flat fading channel with its PDF given by (14). In calculating the channel capacity, the average power gain $\overline{|c_{mi}|^2}$ of each path is assumed to be 1 and the result for $M = 1$ is validated in comparison with that in [19] before using a larger value for M in the equation.

A. Comments on Effect of Finite BCC Step Size

When the BCC step size is finite, it could affect not only the accuracy of beam steering but also the distribution of BCC error $f_\epsilon(\epsilon)$. In the evaluation of the effect of BCC errors above, the distribution of BCC error ϵ was not taken into account as

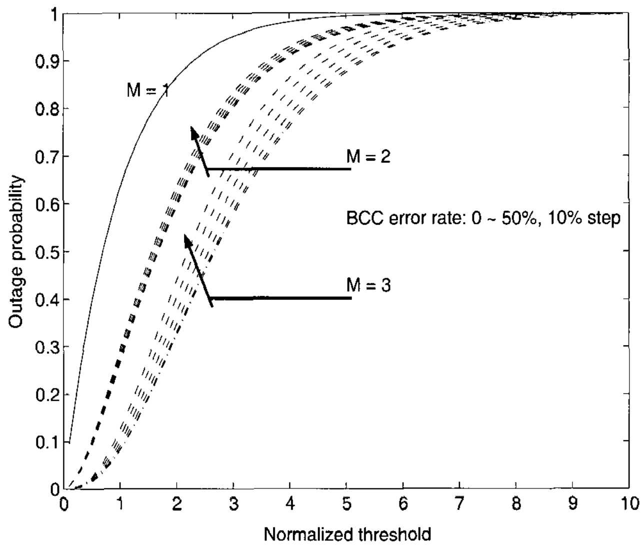

Fig. 9. Service outage probability for $M = 1$, 2, and 3 with BCC errors increasing from 0 to 50% with 10% step in the direction of arrows.

the conditional PDF $f_{|G_{\text{BCC},i}|^2}(\xi|\epsilon)$ of the power gain given a specific BCC error was used. The knowledge of $f_\epsilon(\epsilon)$ could provide further understanding of the effect of BCC errors in implementation-specific scenarios, if desired. For illustration, we performed extensive Monte Carlo simulations in which erroneous BCCs for a BCC error rate $P_{\text{BCC}}(e)$, defined as the number of erroneous BCCs over the total number of BCCs, are randomly selected from a uniform distribution. From this, we noted that the envelope of PDF $f_\epsilon(\epsilon)$ could be roughly approximated with a Gaussian distribution with different variance depending on the value of $P_{\text{BCC}}(e)$. Table 2 shows illustrative values of the mean and variance of the Gaussian distribution numerically obtained by curve fitting of simulation data for $P_{\text{BCC}}(e)$ ranging from 0.05 to 0.25.

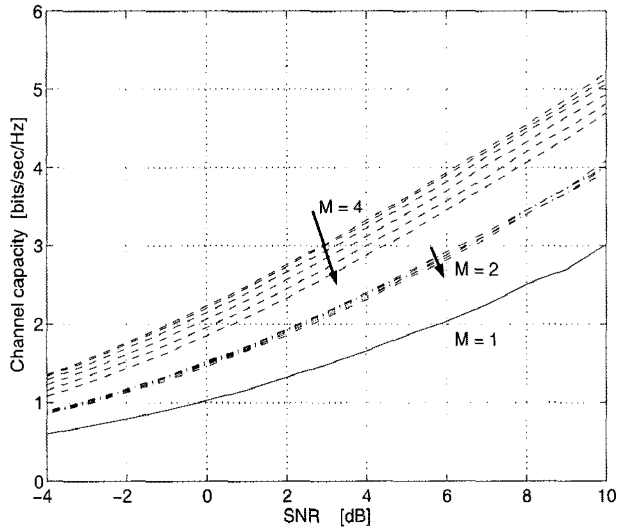

Fig. 10. Channel capacity for $M = 1$, 2, and 5 with BCC errors increasing from 0 to 50% with 10% step in the direction of arrows.

Table 2. Mean and variance of Gaussian-distributed BCC error ϵ.

$P_{\mathrm{BCC}}(e)$		0.05	0.10	0.15	0.20	0.25
Mean	μ_ϵ	−0.07	−0.08	−0.08	−0.07	−0.06
Variance	σ_ϵ	2.41	2.80	3.34	3.98	4.88

VI. CONCLUDING REMARKS

We have presented a new approach to transmit beamforming in MISO FDD systems where the base station uses a sequence of simple beam-control commands transmitted from the mobile one at a time per beam-control period. This method is designed to overcome the challenging requirement on the availability and accuracy of downlink CSI in MISO transmit beamforming and support increasing mobility of users with a single antenna. The effect of BCC errors is also numerically evaluated in terms of transmit power efficiency, service outage probability, and channel capacity.

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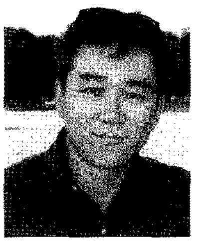

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