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Performance evaluation of distributed-antenna communications systems using beam-hopping

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Summary

Digital beamforming (DBF) techniques are capable of improving the performance of communications systems significantly. However, if the transmitted signals are conflicted with strong interference especially in the direction of the transmitted beams, these directional jamming signals will severely degrade the system performance. In order to efficiently mitigate the interference of the directional jammers, in this contribution a beam-hopping (BH) communications scheme is studied. In the BH communications scheme, only one pair of the beams is used for transmission and it hops from one to the next according to an assigned BH pattern. In this contribution, a range of expressions in terms of the average signal to interference plus noise ratio (SINR) performance have been derived, when both the uplink and downlink are considered. The average SINR performance of the BH scheme and that of the conventional single-beam (SB) as well as multiple-beam (MB) assisted beam-processing schemes have been investigated. Our analysis and results show that the BH scheme is capable of efficiently combating the directional jamming, with the aid of utilizing the directional gain of the beams generated by both the transmitter and the receiver. Furthermore, the BH scheme is capable of reducing the intercept probability of the communications. Therefore, the BH scheme is suitable for communications when several distributed antenna arrays are available around a mobile. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: beamforming; beam-hopping; single-beam; multiple-beam; SINR performance; distributed antenna

1. Introduction

Digital beamforming (DBF) techniques are capable of significantly improving the performance of wireless communications systems by efficiently making use of the directionality of the beams at the transmitter or/and at the receiver [1–4]. In conventional beamforming assisted systems, signals are usually transmitted using the schemes, which form single-beam (SB) or multiple-beams (MB). Furthermore, the beams in the conventional beamforming systems are transmitted in the nearly fixed directions [5,6]. In this case, however if there is a strong interference in the same direction of a transmitted beam, the interference will also be amplified by the beamforming processing operation at the receiver in order to amplify the

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desired signals. Consequently, the communications system's performance might be degraded severely and sometimes the communication might even have to be terminated, as the result of the directional jamming. The above-mentioned case may happen in electronic warfare, when the communications are direction-based and when the jamming signals are also directional.

In the field of beamforming, two typical anti-jamming techniques have been investigated in the literature, namely antenna-nulling [7–9] and interference cancellation [10–12]. The principles behind the antenna-nulling beamforming schemes are that a null is created in the direction of each of the interfering signals, so that the interference from the interfering signals can be efficiently suppressed when amplifying the desired signals. By contrast, when using interference cancellation, because the interference signals often have certain properties different from those of the desired signal, they could be eliminated by a specific processing method. The results of References [7–9] have shown that the antenna-nulling schemes are highly effective, if the desired signals and the interfering signals are from different directions. However, if both the desired signals and the interfering signals are from the same or nearly the same directions, i.e. their directions are highly correlated, then the interference from the interfering signals cannot be effectively mitigated by using the antenna-nulling based beamforming schemes. In the context of the interference cancellation based beamforming schemes, it is well recognized that most of them consist of attractive anti-interference techniques in various situations. However, the beamforming schemes using the interference cancellation demand high-complexity signal processing and hence it is relatively hard to achieve real-time communications.

Some of the proposed beamforming schemes use both the antenna-nulling and the interference cancellation techniques, in order to mitigate interference. In Reference [13] Kohno has combined the antenna-nulling with the interference cancellation techniques, in order to suppress the co-channel interference in a direct-sequence spread-spectrum multiple-access (SSMA) system. In Reference [14] Eken has combined the antenna-nulling techniques with frequency-hopping for combating the following jammers. In these combination schemes a beamformer is first employed at the front stage creating nulls in the directions of the interfering signals, which have direction-of-arrival (DOA) angles different from that of the desired signals. After the nulling operation, an interference canceller is then employed for further suppressing the retaining interfering signals, which have the DOA angles similar to that of the desired signals. The analysis and results in References [13,14] show that these combination schemes constitute a class of attractive interference suppression schemes that are capable of efficiently mitigating the effects of the interfering signals without regarding their DOA angles.

In this contribution, we investigate a novel beam-processing scheme, namely the beam-hopping (BH) communications scheme. In the BH communications scheme, the transmission beams of the transmitter and receiver hop synchronously among a group of preset beams, according to an assigned pattern. Our study and results show that the BH communications scheme constitutes a promising beam-processing scheme, when there exist strong directional interfering signals. In this case, the BH scheme outperforms the conventional SB scheme and the MB scheme.

The rest of the contribution is organized as follows: the BH communications scheme is introduced in Section 2, where the conventional SB communications scheme as well as the MB communications scheme is also outlined. Section 3 provides an analysis of the average signal to interference plus noise ratio (SINR) performance associated with the above mentioned three types of beam-processing communications schemes. Our numerical results are provided in Section 4, and finally in Section 5 we present our conclusions.

2. Beam-Hopping Assisted Beam-Processing Scheme

We assume that there are M DBF arrays in a cell, and each of the DBF array is placed at the outer edge of the cell, as shown in Figure 1. Note that in Figure 1, we distributed six DBF arrays at the six corners of the cell respectively. Moreover, we assume that each cell has a base station (BS) and the DBF arrays in the cell are connected to their corresponding BS using microwave or fiber optic link. As shown in Figure 1, associated with $M = 6$ DBF arrays in a cell, the BS selects the DBF arrays and processes all the transmitted or received data for the DBF. However, if $M = 3$, the cell structure can be designed using the approach proposed by Lee [15], since the cell structure of Reference [15] has the advantages of such a less handoff operations and decreased cochannel interferences [16].

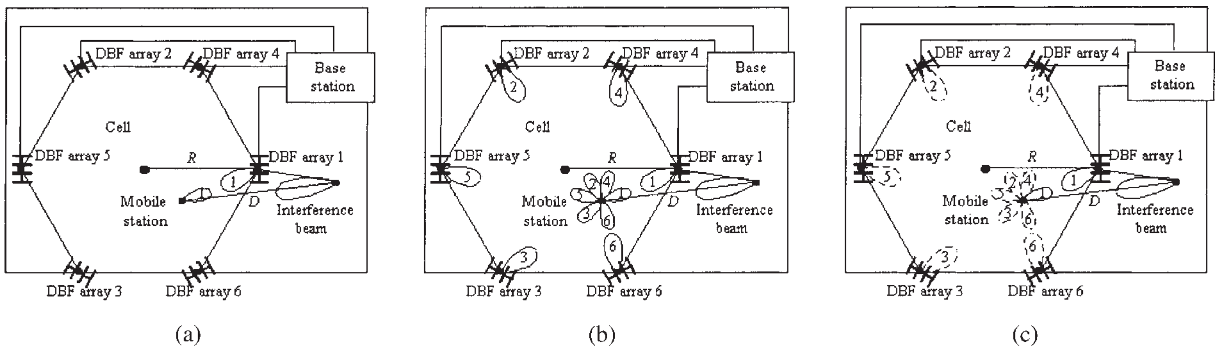


Fig. 1. Demonstrations of the beam-processing schemes using (a) single-beam (SB) scheme, (b) multiple-beams (MB) scheme and (c) beam-hopping (BH) scheme.

Since there are M distributed DBF arrays located at the outer edge of a cell, the transmission can be configured using various schemes. In this contribution three types of beam-processing schemes are considered in our forthcoming discourse, namely the single-beam (SB) processing scheme, the multiple-beam (MB) processing scheme and the beam-hopping (BH) based beam-processing scheme. Let us now describe these beam-processing schemes in detail.

2.1. Single-Beam Scheme

In the conventional SB scheme, the mobile station (MS) in a cell selects only one of the DBF arrays, for example DBF array 1 as shown in Figure 1(a), to communicate with the BS using certain criteria such as maximal received signal power. Therefore, as shown in Figure 1(a), in the conventional SB scheme, the MS forms one beam pointing at the selected DBF array 1. At the same time, the BS sets up one beam pointing at the MS using the selected DBF array 1. According to the above mentioned configurations, we can readily know that in the conventional SB scheme, if there exists a strong interfering signal, emerges in the direction of the beam transmitted from the MS to the selected DBF array 1 or vice versa; the received signal will conflict severe interference that results in significant degradation of the system performance.

2.2. Multiple-Beam Scheme

In the context of the MB scheme, an MS needs to configure M sets of weights. Each of the M sets controls a direction, which points to one of the M DBF arrays. Therefore, in the MB scheme an MS forms M number of beams pointing at M directions. Meanwhile, the BS in the MB scheme forms M beams, one from each of the M DBF arrays, which are pointed at the desired MS. The above-mentioned tasks can be implemented with the aid of the DBF techniques. However, when the MSs position changes, both the MS and the BS have to adapt their weights, in order to retain the beam tracking. Note that, the beam tracking can be achieved with the aid of pilot signals using, for example the adaptive filtering based algorithms [17].

In the MB scheme switched-beam assisted beam-processing schemes are widely used, which switch the transmission beam to the next after transmission for a given duration of time using a beam [18]. When using switched-beam assisted beam-processing, however the probability of an incorrect beam selection is likely to be high, when there is a strong interference in the direction of the transmission. This is the case, even when the decision variable for the desired signal is the output of a matched-filter. This is because the decision variable is constituted by the total received signal strength of $(S+I+N)$ instead of the desired signal strength S alone. Readers interested in the details of this issue are referred to Reference [19], where both the probability of incorrect beam selection and the impact of the incorrect beam selection on the system performance have been analyzed. In this contribution, since we assume that the DBF arrays are distributed at the outer edges of a cell, an alternative but practical beam-processing scheme can be employed. In this alternative beam-processing scheme, the transmission always uses all the M number of beams, as shown in Figure 1(b). The M number of signals received by the

MS or the BS are then combined using the combining scheme, such as maximal ratio combining (MRC), equal gain combining (EGC) or selection combining (SC) etc.

2.3. Beam-Hopping Scheme

In the BH scheme, the BS configures *M* sets of weights to form *M* beams, one from each of the *M* DBF arrays and pointing at the desired MS. Meanwhile, the MS also configures *M* sets of weights to form *M* beams pointing at *M* DBF arrays respectively. By the pilot-aided DBF techniques, the above-mentioned tasks can be implemented, which is similar to the MB scheme case. Furthermore, when the MS moves in the cell, both the MS and the BS adapt their weights to retain the beam tracking.

After both the MS and the BS have established *M* beams, which point at each other accordingly, the BS coordinates a pseudo random BH pattern with the MS with the aid of signaling. Here the BH pattern is a list containing beams of operation in the specific order of hopping, and the BH pattern is known by both the BS and the MS. According to the BH pattern, the BS hops the transmitted beam among the *M* DBF arrays at a determinate hopping rate. At the same time, in order to synchronize with the BSs transmission, the MS also hops its beams at the same hop rate as the BS, according to the same BH pattern of the BS, as shown in Figure 1(c). Figure 2 shows a possible BH arrangement, where the transmission beams are activated from one to another after certain time duration. More specifically, in the first stage, the BS and the MS form *M* beams pointing at each other respectively with the aid of the pilot signal. After that, the BH pattern is arranged and the transmission beams will hop in the sequence of beam 2, beam 3, beam 6 and so on. Therefore, in the BH scheme only one pair of the beams is activated for the transmission at one time. Once the BH pattern is determined, the transmission beams of both the MS and the BS will hop synchronously according to the BH pattern. Hence, the BH scheme does not require a complex beam-switching strategy, which has to be employed by the switched-beam assisted beam-processing schemes.

The BH assisted beam-processing scheme has a range of advantages. First, compared to the SB assisted beam-processing scheme, the BH based beam-processing scheme is able to efficiently mitigate the directional jamming, since the activated transmission beam in the BH scheme is continuously hopping. Hence, both a high beam gain and a low intercept probability of communications can be achieved in the BH scheme. Second, compared to the MB assisted beam-processing scheme, the interception probability in the BH scheme may be much lower, than that in the MB scheme. The low-interception is achieved, since at one time only single pair of beams is activated for transmission in the BH scheme. Furthermore, in the BH scheme the neighboring mobile stations can be assigned with orthogonal hopping patterns, and they can access the network using the spatial multiple-access schemes with the aid of the assigned orthogonal hopping patterns. Hence, the BH based system can be expected to provide a higher system capacity, than the MB based system. Based on the above observations and the results provided in Section 4, it can be shown that the BH assisted beam-processing scheme constitutes a promising scheme, especially in military communications.

In the BH assisted beam-processing scheme either slow beam-hopping (SBH) or fast beam-hopping (FBH) can be employed. In the SBH systems, the BH dwell-time T_h is higher than the data symbol duration *T*. In other words, in the context of the SBH scheme several data symbols are transmitted within one BH dwell-time. In contrast to the SBH scheme, in the FBH systems, the BH dwell-time T_h is lower than the data symbol duration *T*, and one data symbol is transmitted using several BH hops. In comparison with the SBH scheme, the FBH scheme has a higher complexity. However, by using the FBH scheme the received signal can be provided with spatial diversity and, hence the system's performance can be efficiently improved by combining the spatially independent replicas with the

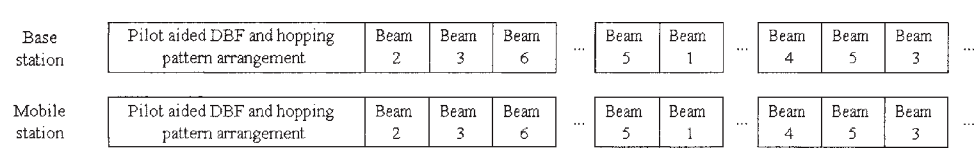


Fig. 2. Example of beam-hopping and synchronization, where the beam-hopping pattern is a list containing beams (channels) of operation in the specific order of hopping.

aid of some optimum or sub-optimum combining schemes [20].

Above, we have described three types of beam-processing schemes, namely the SB, MB and BH schemes. Let us now derive the average SINR associated with these beam-processing schemes in the next section.

3. Average SINR Performance Analysis

In this section, we derive the average SINR expressions for the SB, MB and BH schemes. In our analysis, we assume that there is a strong interfering signal pointing at the desired MS. For the sake of simplicity, we assume that there exists no co-channel interference and no multipath fading. Furthermore, we assume that the beams of the MS and the DBF arrays precisely point at each other respectively. In the context of the BH scheme, the average SINR is derived under the assumption of using SBH, i.e. by assuming that several data symbols are transmitted within one BH dwell-time.

We take a three DBF arrays cell ($M = 3$), for example as illustrated in Figure 3. The cell radius is R, the distance from the interference source to the MS is D, the angle formed from the cell center and the MS to the DBF array 1 is ϕ. $\theta_{I,M}^{Ti}$, $\theta_{T,M}^{I_i}$ and $\theta_{I,T}^{Mi}$ ($i = 1, 2, \ldots, M$) denote the angle formed from the interference source and the MS to the DBF array i, the angle formed from the DBF array i and the MS to the interference source, and the angle formed from the interference source and the DBF array i to the MS respectively. $d_{T,M}^{i}$ and $d_{T,I}^{i}$ ($i = 1, 2, \ldots, M$) denote the distance from the DBF array i to the MS, and the distance from the DBF array i to the interference source respectively. The subscript or superscript T, I and M refer to the DBF array, the interference source and the MS respectively.

3.1. Downlink Performance

3.1.1. Average SINR of the BH scheme

In the context of the BH scheme, we assume that random BH patterns are employed and that each of the M DBF arrays is activated at the same probability for transmitting information with the MS. Consequently, the average SINR of the BH scheme can be expressed as

$$\begin{aligned}\overline{\mathrm{SINR}_{\mathrm{BH}}^{\mathrm{d}}} &= 10\log\left(\frac{1}{M}\sum_{i=1}^{M}\frac{10^{P_{Si}^{d}/10}}{10^{P_{Ji}^{d}/10}}\right)\\ &= 10\log\left(\frac{1}{M}\sum_{i=1}^{M}10^{\frac{\left(P_{Si}^{d}-P_{Ji}^{d}\right)}{10}}\right)\end{aligned} \quad (1)$$

where the superscript d is the indication of downlink, P_{Si}^{d} and P_{Ji}^{d} represent the desire signal's power and the interference plus noise power respectively, received by the ith beam of the MS. For convenience, these power-related variables are expressed in the form of

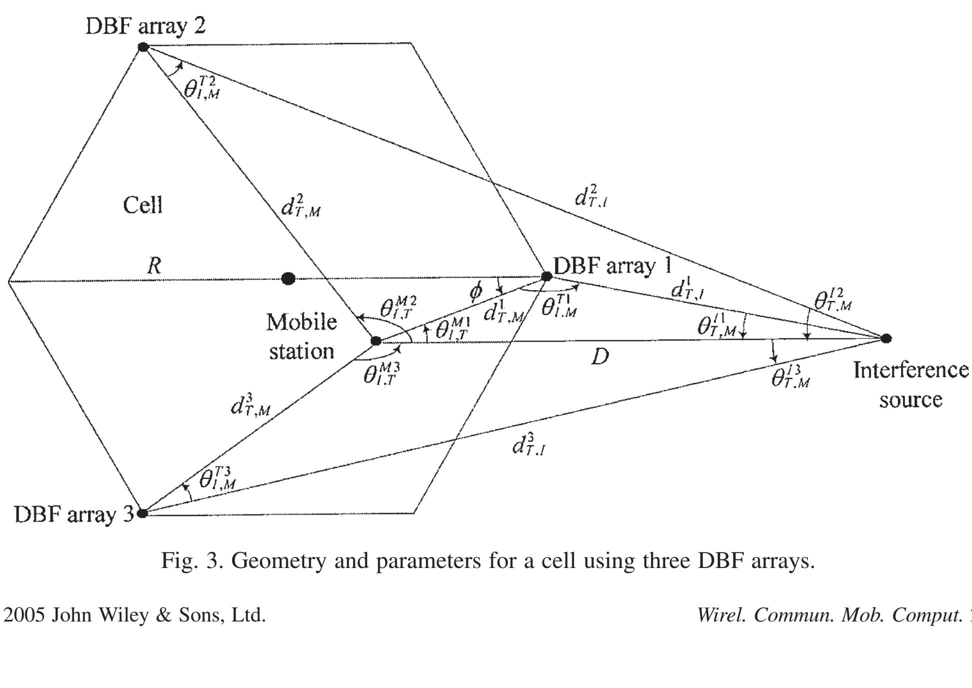


Fig. 3. Geometry and parameters for a cell using three DBF arrays.

decibel (dB) values. Furthermore, in the following all the power-related variables are in the form of dB values, unless specifically indicated. In Equation (1), the power received from the desired signal can be expressed as

$$P_{Si}^{d} = P_T + G_T(0) + G_M(0) - PL\left(d_{T,M}^{i}\right) \quad (2)$$

while the power due to the interfering signal and the background noise can be expressed as

$$P_{Ji}^{d} = P_I + G_I(0) + G_M\left(\theta_{I,T}^{Mi}\right) - PL(D) + N_0 \quad (3)$$

In Equations (2) and (3), P_T and P_I represent the transmitted power of an activated DBF array and the interfering signal respectively, $G_T(\theta)$, $G_M(\theta)$ and $G_I(\theta)$ denote the beam gain functions of the DBF array, the MS and the interfering signal respectively, when the incident angle is θ. The path loss for a transmitter-to-receiver (T-R) distance of l is expressed as $PL(l)$ in Equations (2) and (3). Finally, in Equation (3) N_0 denotes the single-sided power spectral density of the additive white Gaussian noise (AWGN).

3.1.2. Average SINR of the SB scheme

For the SB assisted beam-processing communications scheme, since only a fixed DBF array, for example the DBF array 1, transmits information to the MS, the average SINR can be expressed as

$$\begin{aligned}\overline{\mathrm{SINR}_{\mathrm{SB}}^{\mathrm{d}}} &= P_{S1}^{d} - P_{J1}^{d} = \left(P_T + G_T(0) + G_M(0) - PL\left(d_{T,M}^{1}\right)\right) \\ &\quad - \left(P_I + G_I(0) + G_M\left(\theta_{I,T}^{M1}\right) - PL(D) - N_0\right)\end{aligned} \quad (4)$$

where the variables have the same meaning, as the corresponding variables in Equations (2) and (3).

3.1.3. Average SINR of the SB scheme

Finally, in the context of the MB scheme, since it uses all the M beams, each of the DBF arrays contributes one; to communicate with the MS, the transmitted power from each DBF array should be $P_T - 10\log M$ dB, in order to retain a given total of transmitted power of P_T. Assuming that a combining scheme is employed by the MS in order to combine the signals from the M DBF arrays, the average SINR then can be expressed as [21]

$$\begin{aligned}\overline{\mathrm{SINR}_{\mathrm{MB}}^{\mathrm{d}}} &= 10\log\left[\frac{1}{2}\left(\sum_{i=1}^{M} w_i \sqrt{2 \times 10^{\frac{P_{Si}^{d} - 10\log M}{10}}}\right)^2\right] \\ &\quad - 10\log\left(\sum_{i=1}^{M}\left(w_i^2 \times 10^{\frac{P_{Ji}^{d}}{10}}\right)\right) \\ &= 20\log\left(\sum_{i=1}^{M} w_i \sqrt{10^{\frac{P_{Si}^{d} - 10\log M}{10}}}\right) \\ &\quad - 10\log\left(\sum_{i=1}^{M}\left(w_i^2 \times 10^{\frac{P_{Ji}^{d}}{10}}\right)\right)\end{aligned} \quad (5)$$

where w_i represents the combining weight corresponding to the signal received by the ith beam of the MS. Specifically, when the EGC scheme is assumed, then we have $w_i = 1$ for $i = 1, 2, \ldots, M$. Consequently, Equation (5) can be simplified as

$$\begin{aligned}\overline{\mathrm{SINR}_{\mathrm{MB\_EGC}}^{\mathrm{d}}} &= 20\log\left(\sum_{i=1}^{M} \sqrt{10^{\frac{P_{Si}^{d} - 10\log M}{10}}}\right) \\ &\quad - 10\log\left(\sum_{i=1}^{M} 10^{\frac{P_{Ji}^{d}}{10}}\right)\end{aligned} \quad (6)$$

By contrast, when the MRC scheme is employed, then we have $w_i = 10^{\frac{P_{Si}^{d} - 10\log M - 2P_{Ji}^{d}}{20}}$ for $i = 1, 2, \ldots, M$. Hence, we have

$$\begin{aligned}\overline{\mathrm{SINR}_{\mathrm{MB\_MRC}}^{\mathrm{d}}} &= 10\log\left(\sum_{i=1}^{M} 10^{\frac{P_{Si}^{d} - 10\log M - P_{Ji}^{d}}{10}}\right) \\ &= 10\log\left(\frac{1}{M}\sum_{i=1}^{M} 10^{\frac{P_{Si}^{d} - P_{Ji}^{d}}{10}}\right)\end{aligned} \quad (7)$$

By comparing Equation (1) with Equation (7) it can be shown that, with the aid of the MRC, the MB assisted beam-processing scheme is capable of achieving the same average SINR, as the BH assisted beam-processing scheme, i.e. we have $\overline{\mathrm{SINR}_{\mathrm{MB\_MRC}}^{\mathrm{d}}} = \overline{\mathrm{SINR}_{\mathrm{BH}}^{\mathrm{d}}}$.

Finally, when the SC based combining scheme is employed, the beam output having the maximum SINR value among the M obtained by the MS is selected as the decision variable. Hence, the average SINR can be expressed as

$$\overline{\mathrm{SINR}^{\mathrm{d}}_{\mathrm{MB\_SC}}} = \max\{P^d_{Si} - 10\log M - P^d_{Ji}, \quad \text{for} \quad i = 1, 2, \ldots, M\} \tag{8}$$

3.2. Uplink Performance

The average SINR expressions for the uplink associated with the three beam-processing schemes can be derived using similar approaches as that for the downlink. However, in contrast to Equations (2) and (3), the received power P^{u}_{Si} from the desired signal and the power P^{u}_{Ji} from the interfering signal and noise by the ith DBF array must be expressed as

$$P^{\mathrm{u}}_{Si} = P_M + G_M(0) + G_T(0) - PL\left(d^i_{T,M}\right) \tag{9}$$

and

$$P^{\mathrm{u}}_{Ji} = P_I + G_I\left(\theta^{Ii}_{T,M}\right) + G_T\left(\theta^{Ti}_{I,M}\right) - PL\left(d^i_{T,I}\right) + N_0 \tag{10}$$

where the superscript u is for indicating the uplink, P_M represents the transmitted power by one of the M beams of the MS, while the details of the other variables are referred to the explanations associated with Equations (2) and (3). With the aid of Equations (9) and (10), the average uplink SINR expressions corresponding to the three types of beam-processing schemes concerned can be readily summarized using similar approaches as those for the downlink.

In this section, the average SINR expressions in the context of the beam-processing schemes using SB, MB and BH have been derived, when both uplink and downlink are considered respectively. In the next section a range of numerical results are provided and discussed for comparison among these beam-processing schemes.

4. Numerical Results

In this section, we compare the average SINR performance of the beam-processing schemes using SB, MB and BH, as discussed in the previous sections. Note that in the BH scheme, we assume that random BH patterns are employed and that each of the M DBF arrays is activated at the same probability for transmitting information with the MS. Our numerical results are evaluated based on two typical cell configurations. The first cell configuration is shown in Figure 3, where $M = 3$ DBF arrays are employed. The second cell configuration example is shown in Figure 1, where the $M = 6$ DBF arrays are located at the six corners of the hexagon. Let $\theta^{M1}_{I,T} = \varphi$ and $d^1_{T,M} = d$, then the geometric related parameters for the cell using three DBF arrays can be summarized as follows:

$$d^2_{T,M} = \sqrt{d^2 + 3R^2 - 2\sqrt{3}Rd\cos\left(\phi + \frac{\pi}{6}\right)} \tag{11}$$

$$d^3_{T,M} = \sqrt{d^2 + 3R^2 - 2\sqrt{3}Rd\cos\left(\frac{\pi}{6} - \phi\right)} \tag{12}$$

$$\theta^{T1}_{I,M} = \begin{cases} \arcsin\left(\frac{D\sin\varphi}{d^1_{T,I}}\right) & d > D\cos\varphi \\ \pi - \arcsin\left(\frac{D\sin\varphi}{d^1_{T,I}}\right) & d \le D\cos\varphi \end{cases} \tag{13}$$

$$\theta^{Ti}_{I,M} = \arcsin\left(\frac{D\sin\theta^I_{Mi}}{d^i_{T,I}}\right) \quad \text{for} \quad i = 2, 3 \tag{14}$$

$$\theta^{M2}_{I,T} = \arccos\left[\frac{d\sin\left(\phi + \frac{\pi}{6}\right)}{d^2_{T,M}}\right] + \varphi - \phi + \frac{\pi}{3} \tag{15}$$

$$\theta^{M3}_{I,T} = \begin{cases} 2\pi - \arccos\left(\frac{\left(d^2_{T,M}\right)^2 + \left(d^3_{T,M}\right)^2 - 3R^2}{2d^2_{T,M} \times d^3_{T,M}}\right) - \theta^{M2}_{I,T} & \phi \le \frac{\pi}{6} \\ \arccos\left(\frac{\left(d^2_{T,M}\right)^2 + \left(d^3_{T,M}\right)^2 - 3R^2}{2d^2_{T,M} \times d^3_{T,M}}\right) + \theta^{M2}_{I,T} & \phi > \frac{\pi}{6} \end{cases} \tag{16}$$

$$d^i_{T,I} = \sqrt{\left(d^i_{T,M}\right)^2 + D^2 - 2Dd^i_{T,M} \times \cos\theta^{Mi}_{I,T}} \quad \text{for} \quad i = 1, 2, 3 \tag{17}$$

$$\theta^{Ii}_{T,M} = \pi - \theta^{Ti}_{I,M} - \theta^{Mi}_{I,T} \quad \text{for} \quad i = 1, 2, 3 \tag{18}$$

Note that the geometric related parameters for the DBF array 1, DBF array 2 and DBF array 3 are the same for the cells using three DBF arrays and six DBF arrays, as illustrated in Figures 3 and 1. The other geometric related parameters for the cell using six DBF arrays can be summarized as follows:

$$d^4_{T,M} = \sqrt{d^2 + R^2 - 2Rd\cos\left(\phi + \frac{\pi}{3}\right)} \tag{19}$$

$$d^5_{T,M} = \sqrt{d^2 + 4R^2 - 4Rd\cos\phi} \quad (20)$$

$$d^6_{T,M} = \sqrt{d^2 + R^2 - Rd\cos\left(\frac{\pi}{3} - \phi\right)} \quad (21)$$

$$\theta^{Ti}_{I,M} = \arcsin\left(\frac{D\sin\theta^I_{Mi}}{d^i_{T,I}}\right) \quad \text{for} \quad i = 4, 5, 6 \quad (22)$$

$$\theta^{M4}_{I,T} = \arccos\left[\frac{d\sin\left(\phi + \frac{\pi}{3}\right)}{d^4_{T,M}}\right] + \varphi - \phi + \frac{\pi}{6} \quad (23)$$

$$\theta^{M5}_{I,T} = \arccos\left(\frac{\left(d^2_{T,M}\right)^2 + \left(d^5_{T,M}\right)^2 - R^2}{2d^2_{T,M} \times d^5_{T,M}}\right) + \theta^{M2}_{I,T} \quad (24)$$

$$\theta^{M6}_{I,T} = \arccos\left[\frac{d\sin\left(\frac{\pi}{3} - \phi\right)}{d^6_{T,M}}\right] - \varphi + \phi + \frac{\pi}{6} \quad (25)$$

$$d^i_{T,I} = \sqrt{\left(d^i_{T,M}\right)^2 + D^2 - 2Dd^i_{T,M} \times \cos\theta^{Mi}_{I,T}} \quad \text{for} \quad i = 4, 5, 6 \quad (26)$$

$$\theta^{Ii}_{T,M} = \pi - \theta^{Ti}_{I,M} - \theta^{Mi}_{I,T} \quad \text{for} \quad i = 4, 5, 6 \quad (27)$$

Assuming that the path loss obeys the log-distance path loss model [16], then the path loss can be written as

$$PL(l)(\text{dB}) = \overline{PL(l_0)} + 10n\log\left(\frac{l}{l_0}\right) + X_\sigma \quad (28)$$

when the distance between the transmitter and the receiver is l. In Equation (28) l_0 represents the so-called closed-in reference distance, which is a known received power reference point. n is the path loss exponent and finally, X_σ represents a zero-mean Gaussian distributed random variable having a standard deviation σ expressed in the form of dB. Furthermore, in our numerical evaluation, we assume that the beam gain functions with respect to the DBF arrays, the mobile station (MS) as well as the interfering signal can all be expressed as [22]

$$G(\theta)(\text{dB}i) = \begin{cases} C \times \sin\left(\frac{\pi}{2} \times \left(\frac{\theta}{\theta_w} + 1\right)\right) & \theta \le 2\theta_w \\ -C & \theta > 2\theta_w \end{cases} \quad (29)$$

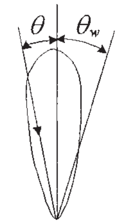


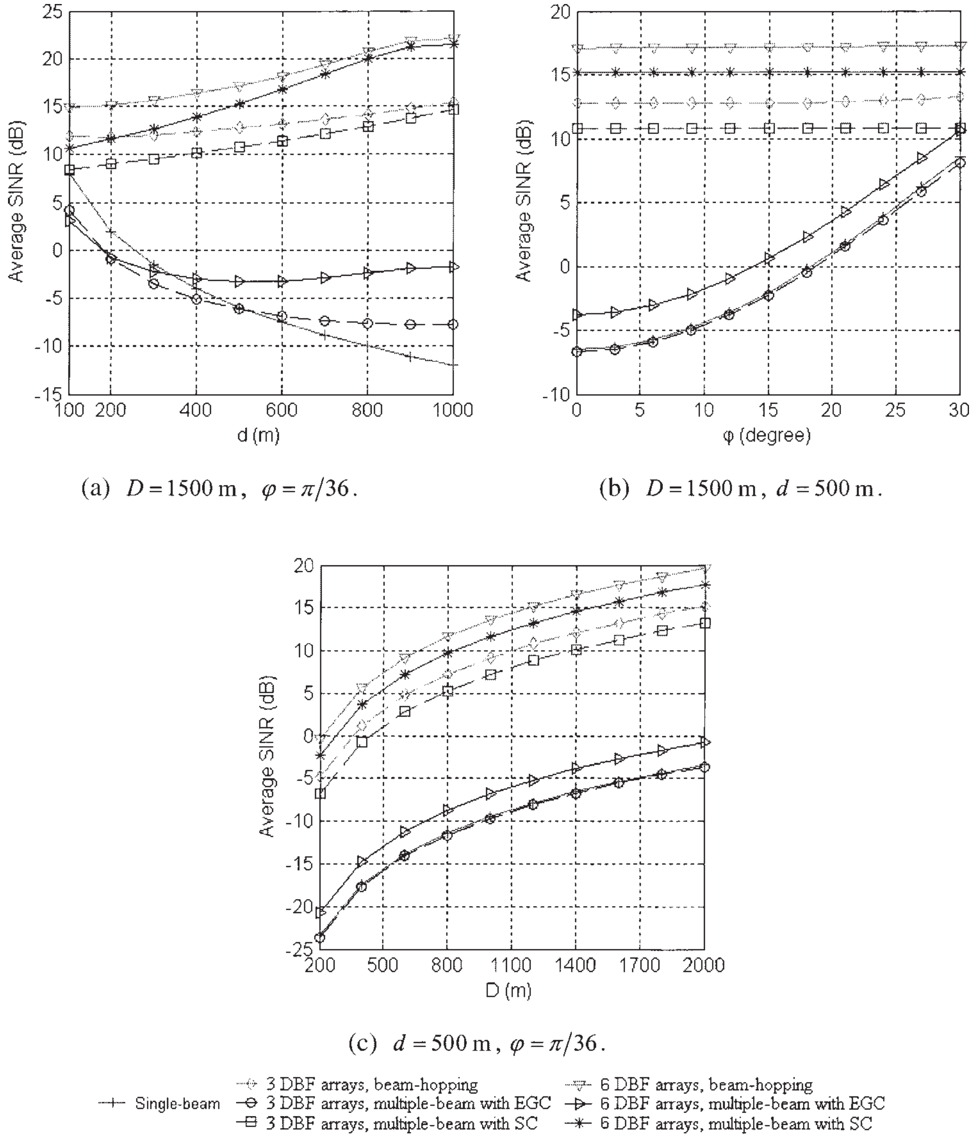
Fig. 4. Beam pattern of the DBF arrays, the mobile station (MS) and the interfering signal, where θ is the incident DOA angle and θ_w is the half beamwidth.

where θ is the incident DOA angle. If $\theta \ge \pi$, then we have $\theta \leftarrow 2\pi - \theta$. Furthermore, in Equation (29) C is a gain coefficient and θ_w is the half beamwidth, as illustrated in Figure 4. Note that, the beam pattern issue is beyond the scope of this paper, hence the details are not considered furthermore in our forthcoming discourse.

In Figures 5 and 6, we demonstrate the downlink and uplink performance comparisons among the three types of beam-processing schemes, namely among the SB, MB and BH schemes respectively. The performance curves were drawn with respect to various values of d, φ and D for both the cell using $M = 3$ DBF arrays and the cell using $M = 6$ DBF arrays. Since the average SINR performance of the BH scheme and the MB scheme using MRC are the same, as illustrated in Equation (7), the average SINR curves corresponding to the MB scheme using the MRC were not distinguished in the figures.

The rest parameters used in Figures 5 and 6 are as follows. The half beamwidths of $G_T(\theta), G_M(\theta)$ and $G_I(\theta)$ were set to be $\pi/6$. Under these conditions, the gain coefficients were computed as $C_T = 20, C_M = 15$ and $C_I = 30$ respectively. Moreover, we had $R = 1000\,\text{m}, \phi = \pi/4, P_T = 30\,\text{dBm}, P_M = 23\,\text{dBm}, P_I = 30\,\text{dBm}$, $N_0 = 6\,\text{dB}, l_0 = 100\,\text{m}, \sigma = 10\,\text{dB}, \overline{PL(l_0)} = 70\,\text{dB}$ and $n = 2$.

Figure 5(a) is drawn against the distance d between the MS and the DBF array 1, Figure 5(b) is evaluated versus the angle φ as shown in Figure 3, and finally in Figure 5(c), we show the effect of the distance D, between the MS and the interference source, on the average SINR performance. From Figure 5 corresponding to the downlink, we observe that the average SINR achieved by either the BH scheme or the MB scheme using SC is significantly higher, than that achieved by the SB scheme, when there is a strong directional interference. However, the downlink SINR performance of the MB scheme using the EGC is improved insignificantly, comparing with the SB



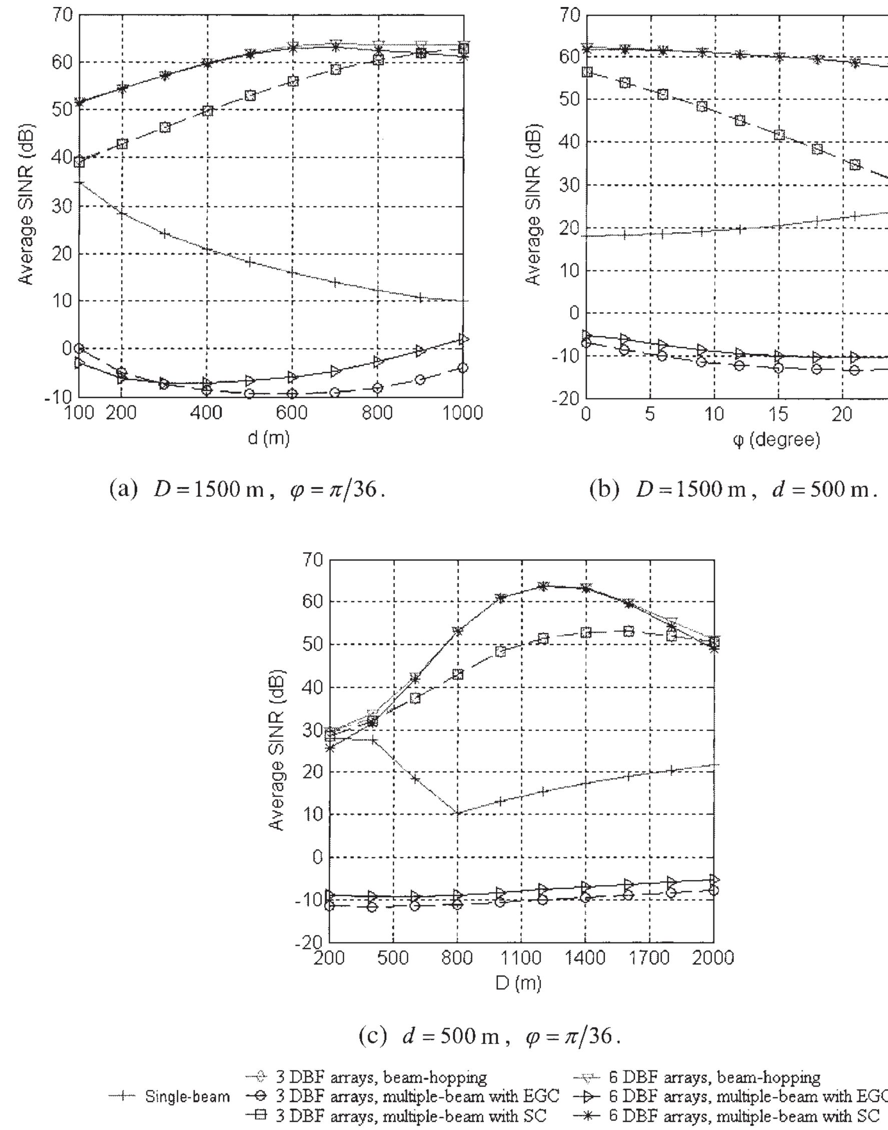
(a) $D = 1500\,\text{m}$, $\varphi = \pi/36$.

(b) $D = 1500\,\text{m}$, $d = 500\,\text{m}$.

(c) $d = 500\,\text{m}$, $\varphi = \pi/36$.

Fig. 5. Downlink average SINR performance for the three types of beam-processing schemes, namely the SB, MB and BH schemes, when a cell using either three DBF arrays or six DBF arrays are assumed. In Figure 5(a), d represents the distance between the MS and the DBF array 1, in Figure 5(b), φ is the angle between the line connecting the MS and the DBF array 1 and the line connecting the MS and the interference source, finally, in Figure 5(c), D represents the distance between the MS and the interference source.

scheme. This is because, when using EGC, one of the combined beams by the MS is always severely interfered by the strong interfering signal and the combined signal always contains the whole power from the interfering signal. Consequently, when using EGC, the average SINR achieved by the MB scheme is low. Furthermore, according to Figure 5(a), (b), (c), the BH scheme and the MB scheme using MRC outperform all the other types of beam-processing schemes and achieve the highest average SINR value. Note again that, according to our analysis carried out in the previous Section 4, both the BH scheme and the MB scheme using MRC achieve the same average SINR performance. Furthermore, Figure 5(a), (b), (c) show that the average SINR performance using $M = 6$ DBF arrays is generally better than that using $M = 3$ DBF arrays. This phenomenon can be readily understood, since with a higher number of beams, the probability of hit due to the interfering signal in the BH scheme is lower. In the context of the MB scheme,



(a) $D = 1500$ m, $\varphi = \pi/36$.

(b) $D = 1500$ m, $d = 500$ m.

(c) $d = 500$ m, $\varphi = \pi/36$.

Fig. 6. Uplink average SINR performance for the three types of beam-processing schemes, namely the SB, MB and BH schemes, when a cell using either three DBF arrays or six DBF arrays are assumed. In Figure 6(a), d represents the distance between the MS and the DBF array 1, in Figure 6(b), φ is the angle between the line connecting the MS and the DBF array 1 and the line connecting the MS and the interference source, finally, in Figure 6(c), D represents the distance between the MS and the interference source.

a higher number of beams imply a higher number of diversity components, which also results in improved performance, when the MRC or SC is employed for combining the diversity components.

More specifically, as shown in Figure 5(a), the downlink SINR performance for the SB scheme degrades rapidly, when increasing the distance d between the transmitter and the receiver. This is the result of the path loss, which makes the received power by the DBF array 1 from the desired signal become weak, when increasing the distance d. In contrast to the SB scheme, the downlink SINR performances for both the BH scheme and the MB scheme using SC improve slightly, when the distances from the MS to most of the DBF arrays become shorter. From Figure 5(b), we observe that the average SINR performance of the SB scheme becomes worse, when decreasing the value of φ, i.e. as shown in Figure 3, when the interference source moves close to the direct path between MS and DBF array 1. In

Figure 5(c) the downlink average SINR is evaluated versus the distance between MS and the interference source. As expected, the average SINR performance improves, when increasing the value D. From Figure 5, we could also observe that the performance of BH scheme outperforms that of MB scheme, because for the BH scheme, since it only uses one beam at one time to communicate, the transmitted power of one beam is larger than that of the MB scheme.

In Figure 6(a), (b), (c), we demonstrate the uplink average SINR performance. As in Figures 5, 6(a) is drawn against the distance d between MS and DBF array 1, Figure 6(b) is evaluated versus the angle φ, as shown in Figure 3, and finally, in Figure 6(c) we show the effect of the distance D, between the MS and the interference source, on the average SINR performance. Generally speaking, the results of these figures show that both the BH scheme and MB scheme using SC outperform the SB scheme. However, as shown in these figures, there may occur intersects between some curves. The crossovers occur mainly because we assume that the strong interference was directed to MS instead of DBF array 1. Since one of the combined branches in the MB scheme contains a very low SINR value due to the interfering signal, the uplink average SINR performance of the MB scheme using EGC is very poor and, in some cases it is even poorer, than that of the SB scheme, as shown in Figure 6(a), (b), (c). Furthermore, because the SINR of the poorest combined branch changes irregularly in response to the variation of the parameters, the uplink average SINR of the MB scheme using EGC varies in a wave-like manner. This phenomenon becomes explicit in the case, when each cell uses six DBF arrays. Similar to Figure 5, the results in Figure 6 show that the uplink average SINR performance of the cell using six DBF arrays, in most cases, is superior to that of the cell using three DBF arrays. From Figure 6(b), we also observe that SB scheme, BH scheme and MB scheme with SC have nearly the same performance when $\varphi = \pi/6$, this is because we assumed that the half beamwidth θ_w is $\pi/6$. When $\varphi = \pi/6$, the signal received by the DBF array 1 becomes the strongest in the cell with three DBF arrays. In addition, in Figure 6(c), we could see that the curves wave irregularly, this is because when D increases, the strong interference source first becomes closer to the DBF array 1 and then moves further away from all the DBF arrays. Also, note that when the position of the strong interference source changes, the other parameters, such as the distance from the interference to the DBF arrays and the incident angles of the interference change accordingly.

5. Conclusions

In this contribution, a novel beam-processing scheme, namely BH scheme, has been studied. The average SINR performance of the BH scheme and that of the conventional SB as well as MB assisted beam-processing schemes have also been investigated. A range of expressions in terms of the average SINR performance have been derived, when both the uplink and downlink are considered. With the aid of the derived expressions, we have presented a range of numerical results in the context of the beam-processing schemes considered. From our analysis and numerical results, we can conclude that the BH scheme is capable of combating strong directional interference. It significantly outperforms the SB assisted beam-processing scheme. It is also capable of achieving better performance than MB assisted beam-processing using both EGC and SC based beam-combining schemes. Both the BH scheme and the MB scheme using the MRC based beam-combining achieve the same average SINR performance. Therefore, BH scheme constitutes one of the promising schemes, which are suitable for the communications systems employing distributed antenna arrays.

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