On the Effects of Misalignment and Angular Spread on the Beamforming Performance

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Invited Paper

***Abstract*— This paper addresses several important issues regarding the operation of switched and adaptive beamforming techniques. The performances of these techniques are compared using arrays that employ various numbers of directional antenna elements. The effect of misalignment between the direction of arrival of the incoming signal and the receiver beam-pattern is analyzed. The performance degradation due to the angular spread of the arriving signal is also investigated. It is shown that the decrease in the beamforming gain due to the beampointing error is much more severe than due to the angular spread. In the paper, it is also pointed out that the performance of the switched beamforming approaches the adaptive one only when the target space is scanned in very small spatial increments.**

I. Introduction

Recent advances in process technologies and low cost integration solutions for 60 GHz technology have promoted a great deal of momentum from academia, industry and standardization bodies towards 60 GHz radio, which has emerged as one of the most promising candidates for multi-gigabit wireless indoor communication systems [1]. There are a number of key features that make 60 GHz technology particularly attractive over existing communication systems [2]. The recent popularity of the 60 GHz technology is owed to the huge unlicensed bandwidth (up to 7 GHz) available worldwide. While this is comparable to the unlicensed bandwidth allocated for ultra wideband (UWB) systems [3], 60 GHz bandwidth is advantageous in that it is continuous and less restricted in terms of power limits. This is due to the fact that UWB systems are underlay systems, and hence, they are subject to very strict and different regulations worldwide [4]. The large bandwidth at 60 GHz band is one of the widest unlicensed bandwidths that have been allocated in history. Furthermore, 60 GHz regulation allows a much higher transmit power compared to other existing wireless local area network (WLAN) and wireless personal area network (WPAN) systems. The high transmit power is necessary to overcome the relatively higher path loss at 60 GHz. Although the high path loss seems to be a disadvantage of 60 GHz, since it confines the 60 GHz operation to the inside of a room in an indoor environment, the effective interference levels for 60 GHz are less severe than those systems located in the congested 2-2.5 GHz and 5-5.8 GHz bands. In addition, in 60 GHz systems, higher frequency reuse can be achieved in indoor environments leading to very high throughput networks. The compact size of the 60 GHz radio also permits multiple antennas solution at the user terminal, which is difficult if not impossible at lower frequencies.

In spite of the various advantages offered, 60 GHz based communications suffer from a number of critical problems that must be resolved. Being different from UWB applications, the IEEE 802.15.3c systems are considered to provide gigabit data rate and longer operating distances. At this rate and range, it will be a non-trivial task for 60 GHz systems to provide a sufficient power margin to ensure a reliable communication link. In addition, delay spread of the channel under study is another limiting factor for high speed transmissions. Large delay spread values can easily increase the complexity of the system beyond the practical limit for equalization. One might use high gain antennas to overcome the poor link margin, but this has limited usefulness especially in WPAN scenario since the shadowing effects such as the blockage due to human body can attenuate the line-of-sight (LOS) signal by 18-30 dB [5], [6]. Also, a slight misalignment of the transmitter (Tx) and receiver (Rx) antennas could potentially lead to a significant increase in the delay spread [6]. In this respect, the use of antenna arrays to increase the directivity or gain of the 60 GHz communication systems becomes highly desirable to improve the link margin and to control the delay spread of the radio channel.

The remainder of the paper is organized as follows: Section II describes the system model used in the analyses throughout this paper. Section III discusses the differences between the switched and adaptive beamforming and compares their performances. Section IV analyzes the effects of misalignment between the incoming signal and the receiver beam; Section

V studies the effects of angular spread of the received signal; finally, in Section VI conclusions wrap up this paper.

II. System Model

In this paper, we consider rectangular arrays with an array factor given by [7]

$$AF(\theta,\phi) = \frac{\sin(M\psi_x/2)}{M\sin(\psi_x/2)} \cdot \frac{\sin(N\psi_y/2)}{N\sin(\psi_y/2)} \ , \quad (1)$$

where M and N are the number of elements in x and y dimensions, respectively. The variables ψ_x and ψ_y are given by

$$\psi_x = kd_x sin(\theta)cos(\phi) - kd_x sin(\theta_0)cos(\phi_0) \ , \quad (2)$$

and

$$\psi_y = kd_y sin(\theta)sin(\phi) - kd_y sin(\theta_0)sin(\phi_0) \ , \quad (3)$$

where θ, ϕ, θ_0 and ϕ_0 are the elevation angle, azimuth angle, pointing elevation angle and pointing azimuth angle, respectively. The variables d_x and d_y denote the distances between the elements in x and y directions, respectively.

It is aimed that the array has the strongest coverage around $\theta = 90°$, which is a desired property in many smart antenna applications [8]. Therefore, the antenna elements are positioned onto the xz plane, such that the narrowest peak that can be generated by the array is directed towards this elevation. The distance between the antenna elements in both dimensions is equal to $\lambda/2$, where λ is the free space wavelength of the received signal.

The radiation pattern of each array element is given by

$$EP(\theta,\phi) = sin(\theta) \cdot cos(\phi) \ , \quad (4)$$

which is shown in Fig. 1. The overall array pattern is obtained according to the principle of pattern multiplication, which can be expressed as [9]

$$B(\theta,\phi) = AF(\theta,\phi) \cdot EP(\theta,\phi) \ . \quad (5)$$

III. Adaptive vs. Switched Beamforming

The main objective when forming a beam is to align it with the incoming signal as closely as possible. In switched beamforming, the directions to which the beam can be steered are limited, whereas in adaptive beamforming, the receiver beam can be steered to the exact direction of the incoming signal. The limited number of possible directions in switched beamforming causes an inevitable mismatch between the incoming signals and the receiver beams. This fact results in a performance degradation compared to adaptive beamforming.

A number of simulations were done in order to determine the properties of the beams that are formed and to investigate the performance of the beamforming operation. In these simulations, both adaptive beamforming and switched beamforming cases were considered, and their performances were compared. In both elevation and azimuth dimensions, the coverage is limited to between $\theta = 30°$ and $\theta = 150°$, because this is the range where most of the received signals are expected to arrive. It is also important to note that mainly because of the elemental pattern employed, which has nulls at $\theta = 0°$ and $\theta = 180°$ as well as $\phi = 90°$ and $\phi = 270°$, the beams directed towards outside the given range have little power, and hence, they have a negligible contribution to the system performance.

In the simulations regarding the switched beamforming, the possible directions were taken as $\theta = 90° \pm k \cdot 15°$, and $\phi = 0° \pm k \cdot 15°$, where $-4 \leq k \leq 4$, in the first part; and as $\theta = 90° \pm k \cdot 30°$, and $\phi = 0° \pm k \cdot 30°$, where $-2 \leq k \leq 2$, in the second part. In adaptive beamforming, the receiver beam is assumed to match the direction of the incoming signal as long as it is inside the target range.

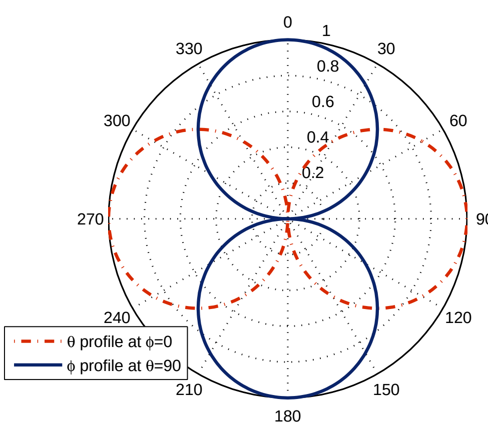

Fig. 1. The radiation pattern each array element.

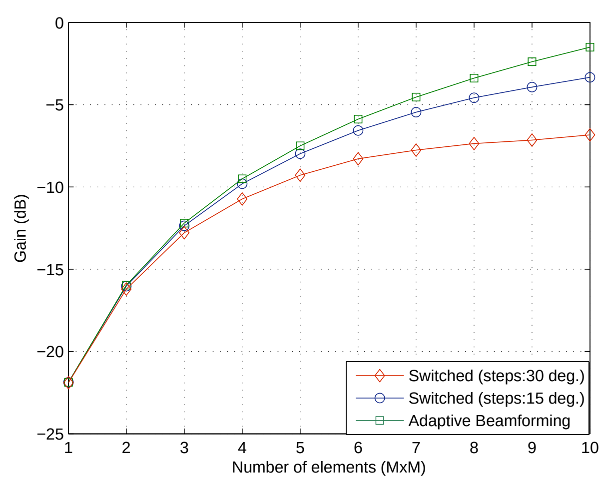

Fig. 2. Gain vs. number of elements in the array (MxM).

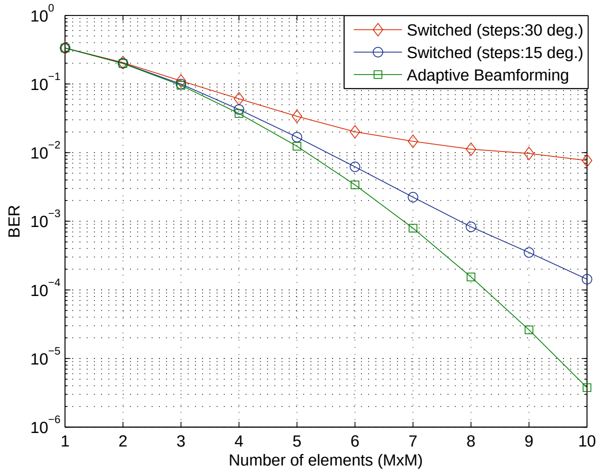

Fig. 3. BER vs. number of array elements ($M \times M$).

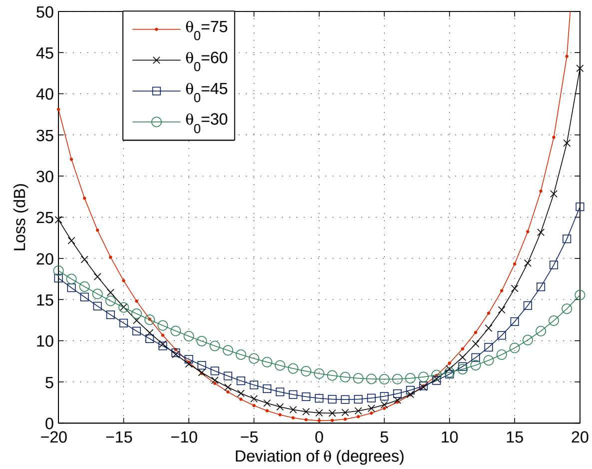

Fig. 4. Loss in power vs. deviation of the received signal from the focus of the beam in θ dimension.

The first simulation analyzes the effect of the number of array elements, where all the arrays considered are square arrays ($M = N$). In order to be able to make a fair comparison, the total power of arrays with different number of elements is kept the same (equal to the normalized total power of the 10×10 array). The total power of the beam is given by [9]

$$P(\theta, \phi) = \int_0^{2\pi} \int_0^{\pi} \left|g(\theta, \phi)\right|^2 sin(\theta)\, d\theta\, d\phi \ , \tag{6}$$

where $g(\theta, \phi)$ is the radiation pattern. The values demonstrated in Figs. 2 and 3 are obtained by averaging the gains corresponding to all possible directions of arrival.

Looking at the gain vs. number of elements curve in Fig. 2, it is very important to observe that the beamforming gain relative to a single antenna case is directly proportional to the total number of elements in the array, *i.e.*

$$G_{bf}(M) = G_{bf}(1) + 10\, log(M^2) \ . \tag{7}$$

Hence, the gain is 20 dB higher for a 10×10 configuration compared to a single antenna. The reason for this fact is that the half power beamwidth (HPBW) of the receiver beam becomes smaller, i.e. the beam becomes more directive, as the number of array elements increases, which leads to a stronger match between the incoming signal and the receiver beam. From Fig. 2, it is apparent that switched beamforming with an angular step of $15°$ in both dimensions yields closer results to adaptive beamforming relative to $30°$ steps because of the higher spatial resolution in the former case. It is also noteworthy that the gain difference between the switched and adaptive beamforming cases becomes more evident for higher number of elements.

Fig. 3 shows the bit error rates (BER) obtained for switched and adaptive beamforming with BPSK modulation at an E_b/N_0 value of 10 dB. For visual purposes, the power of the 10×10 array is increased in such a way that it yields the BER value corresponding to the unity gain at 10 dB, and the power levels of the arrays with less number of elements are adjusted accordingly. It should be noted that for a high number of elements, there is a remarkable BER performance difference between the adaptive and switched beamforming cases.

IV. Effect of Misalignment Between the Incoming Signal and the Receiver Beam

The performance of the beamforming operation is directly related to how closely the incoming signal and the receiver beam are matched to each other. In switched beamforming, a misalignment can occur frequently, and in adaptive beamforming, there might be slight beampointing errors due to insufficient knowledge about the angle of arrival or inaccurate phase shifting between the antenna elements [10]. Therefore, it is worth to have a close look at the effect of deviation of the incoming signal from the receiver beam.

In Fig. 4, the power loss experienced due to the mismatch is investigated for the elevation dimension. In the corresponding simulation, the array employed is of size 8×8. The azimuth of the receiver beams is fixed at $0°$, and their elevations are $\theta = 90° - k \cdot 15°$, where $1 \leq k \leq 4$. In each case, the deviations are bound to a rather wide range of ± 20 degrees. An observation of Fig. 4 reveals that the loss curves are not symmetric around θ_0. This fact is caused by the beamshape that is not symmetric around the focus of the beam. The asymmetry is a result of the array factor that widens towards $\theta_0 = 0°$. The widening phenomenon can be examined by checking the corresponding HPBWs, which are $13.4°, 14.9°, 18.3°$, and $25.8°$, respectively, for the elevations under consideration. It should be also noted that at high deviation angles, the losses

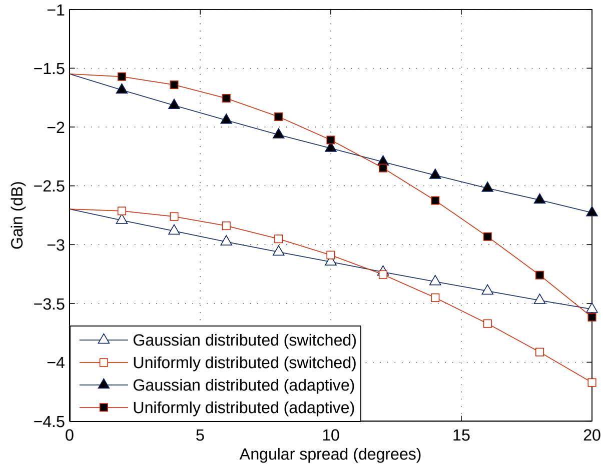

Fig. 5. Gain vs. angular spread (in both θ and ϕ dimensions) of the received signal; both Gaussian and uniform distribution cases are plotted.

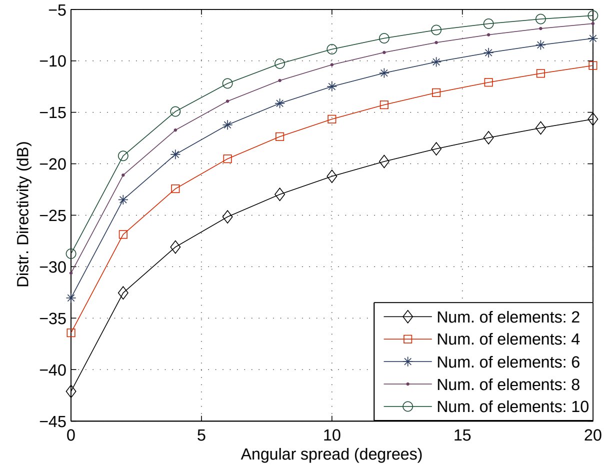

Fig. 6. Distributed directivity vs. angular spread (in both θ and ϕ dimensions) of the received signal.

for $\theta_0 = 30°$ are not as large as the losses encountered for $\theta_0 = 75°$. Again, the reason is that the beam directed to $30°$ is wider, and hence, its gain does not drop as sharply as the gain of the $\theta_0 = 75°$ beam.

V. Effect of Angular Spread of the Incoming Signal

In practical implementation, the performance of beamforming may not be perfect even if the receiver beam of the array is exactly matched with the main direction of arrival of the incoming signal. The reason behind this fact is that the incoming signal may have an angular spread, which the receiving array cannot follow. The angle of arrival can be generally considered to have either a Gaussian or a uniform distribution around the main direction [11]-[13].

A simulation is performed to quantify the effect of the angular spread on the system performance. An 8×8 array is considered, and the values are averaged over all possible directions of arrival. In Fig. 5, the effect of angular spread (in both dimensions) on the beamforming gain is presented for both switched and adaptive beamforming cases. It is seen that the decrease in gain with increasing angular spread is rather linear if the spread has a Gaussian distribution. It should also be noted that the uniform distribution yields a higher gain as long as the angular spread does not exceed roughly 10 degrees. A significant conclusion can be drawn if the curves in Fig. 4 and in Fig. 5 are compared. Apparently, the losses in gain that occur due to the angular spread around the main direction are much lower than the losses caused by the deviation of the main direction.

The decrease in beamforming gain with angular spread can also be indirectly estimated by checking the distributed directivity of the receiver beams, which is given by [14]

$$D = \frac{\int_0^{2\pi}\int_0^{\pi} S(\theta,\phi)\left|g(\theta,\phi)\right|^2 sin(\theta)\, d\theta\, d\phi}{(1/4\pi)\int_0^{2\pi}\int_0^{\pi}\left|g(\theta,\phi)\right|^2 sin(\theta)\, d\theta\, d\phi}\ , \tag{8}$$

where $S(\theta,\phi)$ is a function that describes the target area on the incoming signal. In the case of $20°$ angular spread, the $S(\theta,\phi)$ function can be specified as $[\theta_0 - 10° < \theta < \theta_0 + 10°, \phi_0 - 10° < \phi < \phi_0 + 10°]$. In Fig. 6, the distributed directivity values are presented for various numbers of elements at uniform angular spreads up to $20°$. Apparently, the distributed directivity increases with increasing angular spread, however it has a decreasing slope. The decrease in the slope is an obvious indicator of the fact that the resulting gains will be lower for high angular spreads compared to low spread cases, and therefore, it validates the decrease in the gains presented in Fig. 5.

Our final simulation aimed at looking at the BER performance of the receiving array with and without angular spread for various numbers of antenna elements. The incoming signal is assumed to arrive from any direction inside the target range, and the gain values obtained are averaged over all possible directions. Fig. 7 presents the BERs obtained with BPSK modulation for arrays of various sizes, including a single antenna case, for increasing E_b/N_0 values. In this figure, it is seen that the increase in the number of elements results in a decreased BER, which is an explicit evidence of beamforming gain. On the other hand, it is also observed that increasing the angular spread from 0 to 50 degrees has no effect on the error probability for a single antenna. For any higher number of antennas, the BER is worse when there is an angular spread.

Through the simulations, angular spread is shown to be a factor that degrades the beamforming gain. It could provide *diversity gain*, however, if a number of signals that arrive from different directions and undergo different amounts of fading

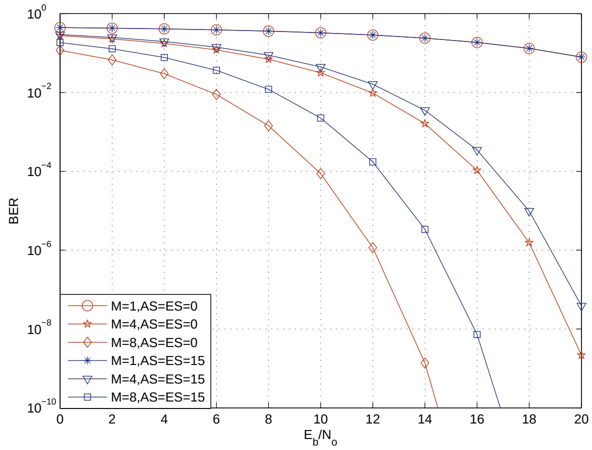

Fig. 7. BER vs. E_b/N_0 for different numbers of array elements with and without angular spreads.

were combined properly (*e.g.* using maximum ratio combining (MRC)) by the receiving array.

VI. Conclusion and Future Work

In this paper, the performances of the switched beam and adaptive beamforming techniques are investigated, and it is shown that the adaptive beamforming always outperforms the switched beam approach. However, this comes at the expense of a higher computational complexity. It is demonstrated that the misalignment between the incoming signal and the receiver beam causes a degradation in the beamforming performance in terms of gain losses. The angular spread of the received signal is shown to be another factor that degrades the performance, but a comparison between these two negative factors revealed that the misalignment has a much more destructive effect. Related future work includes developing an analytical framework for the performance of switched and adaptive beamforming in the presence of misalignment and angular spread.

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