A Simple Adaptive Beamformer for Ultrawideband Wireless Systems

Wasim Q. Malik, Ben Allen, and David J. Edwards

Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK
Email: {wasim.malik, ben.allen, david.edwards}@eng.ox.ac.uk

***Abstract* — This paper introduces a simple beamformer for ultrawideband (UWB) wireless networks. The architecture consists of a two-element antenna array, a phase shifter and a signal combiner. The performance of the proposed beamformer is analyzed in terms of radiation pattern characteristics over the FCC's defined operating band for UWB communications devices. It is shown that this simple architecture can provide useful interference rejection and range extension capabilities for high data-rate UWB wireless networks. In particular, it is shown that the radiation pattern characteristics of the proposed sub-optimal beamformer remain beneficial over the allocated UWB band, even given its low complexity and implementation cost.**

***Index Terms* — Antenna array, beamforming, ultrawideband (UWB).**

I. Introduction

Ultrawideband (UWB) wireless systems have attracted much attention in recent years as a means of providing a short range, high data rate wireless solution [1, 2]. In 2002, the FCC released unlicensed radio spectrum primarily between 3.1–10.6 GHz for UWB transmissions adhering to effective isotropic radiated power (EIRP) limits of -41.6 dBm/MHz and with fractional bandwidths of over 20% or absolute bandwidths of over 500 MHz [3]. Extensive applications of UWB technology in wireless personal area and sensor networks have been cited, in addition to radars and imaging systems [1].

With the above mentioned frequency allocation, interference to and from other spectrum users, such as users of the 5 GHz UNII and ISM bands, will exist, as well as interference between other UWB networks within the proximity. Furthermore, with the useable transmission range restricted to approximately 10 m that results from the allowable EIRP and associated data rate required by the target applications [4], it would seem natural to seek solutions that facilitate interference mitigation together with providing range extension.

Candidate interference mitigation techniques include the following [5]: medium access control solutions; adaptive filtering; antenna diversity based techniques [6]; and beamforming [7]. An extension in the range, while maintaining a given data rate, can be achieved by increasing either the EIRP; receiver sensitivity; or the antenna directivity with directional antennas or beamformers.

Amongst the above techniques, beamforming provides both range extension and interference mitigation. Thus, this paper introduces a simple beamformer that provides both interference mitigation and range extension in the context of UWB wireless networks. A common perception of beamformers is, however, that they are complex and costly to implement, as has been concluded for many cellular telephone applications. Obtaining satisfactory performance over a fractional bandwidth of almost 110%, corresponding to a full-band UWB system operating in the FCC-allocated 3.1–10.6 GHz frequency range [3], is also commonly considered to significantly increase complexity. Indeed, the wideband beamforming architectures introduced in [8, 9] require a large number of antenna elements and significant signal processing capability compared to that required for narrowband applications. Such architectures would be unacceptable for the consumer electronics market, where cost and complexity should be minimized. One of the reasons for the complexity of these techniques is that stringent design constraints, such as sidelobe level, beamwidth etc., are often placed upon the array pattern characteristics.

This paper shows that, without such non-essential constraints, a very simple architecture can provide performance enhancement for consumer applications. Thus, the main contribution of this paper is the proof of concept of a simple sub-optimal beamformer operating over the FCC UWB band that provides both interference mitigation and range extension. It is shown that a satisfactory array pattern is retained over the allocated UWB band. The beamforming operation is considered in the receive mode in order to avoid the complications related to the EIRP restriction in the FCC regulations, which would require active power control and feedback in order to overcome interference issues.

The remainder of this paper is organized as follows. Section II provides a detailed description of the beamformer architecture. Section III analyzes the performance of the beamformer over the UWB band, studying the impact of various parameters. Finally, Section IV draws conclusions from the analysis.

II. Beamformer Architecture

The proposed beamformer consists of two omni-directional antennas in the azimuth plane, a quantized phase-shifter and a combiner circuit, as shown in Figure 1. It is assumed that the antenna element characteristics remain stable over the frequency range of 3.1–10.6 GHz. It is also assumed that the phase-shifter provides a constant phase shift over these frequencies. Furthermore, we use a phase-shifter with a 3-bit quantizer with steps *of* $\pi/4$ radians in the range $[-\pi, \pi]$ radians. The signal combiner is also assumed to be frequency invariant over these frequencies.

It is noted here that several of these assumptions provide significant challenges for the UWB system designer. In particular, a frequency invariant phase-shifter such as a tapped delay line is likely to be particularly challenging, although microwave devices based on microelectromechanical systems (MEMs) that fulfill this role are now becoming available [10]. Similarly, the design of UWB antennas with frequency-invariant radiation characteristics is a complex problem [11]. For the purpose of this discussion, however, we assume ideal system components and focus on the array architecture and resulting beam patterns.

As the array consists of two omni-directional elements, it is able to either steer the main beam or a null to the required azimuth angle over the full 360° range. In order to facilitate the steering of a null, a frequency-invariant signal inverter is connected between the phase shifter and combiner, and thus the signals are subtracted from each other.

The inter-element spacing, d, is assumed to be 4 cm. This spacing is chosen because it corresponds to the inherent spatial resolution of a UWB signal, occupying the FCC allocated band, with 7.5 GHz bandwidth. It also provides a reasonably compact antenna array design, which is attractive for device implementation. Furthermore, this d is equivalent to approximately 0.4λ and 1.4λ for the lowest (3.1 GHz) and highest (10.6 GHz) frequency of the signal spectrum. As the impact of antenna coupling is negligible for $d \geq 0.4\lambda$ [12], we do not consider mutual coupling for the purpose of this investigation.

Although this beamformer can adapt to the prevailing signal conditions, it does not require a complex algorithm for adaptation, and simply adapts by stepping through the eight phase settings in beam steering mode then repeating

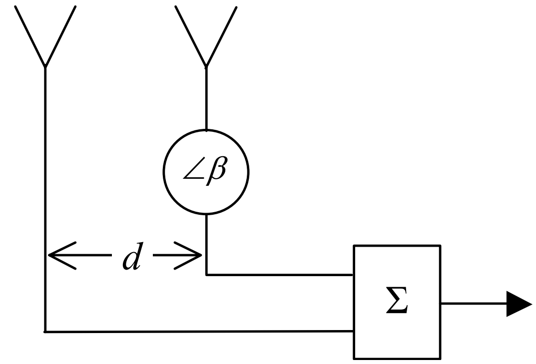

Fig. 1. Architecture of the dual-element beamformer.

this operation in the null steering mode. The mode and phase setting that provides either the highest signal-to-interference-plus-noise ratio (SINR) or the lowest bit error rate (BER) or packet error rate (PER) is then chosen. This adaptation process is repeated periodically, according to how fast the signaling conditions are deemed to change. Assuming the signal conditions are sampled once per data frame, a total of 16 frames are required for the correct setting to be chosen. This interval can be extended if a running average over several samples is employed; this, however, will increase the adaptation time. Assuming the transmission structure of MB-OFDM [13], adaptation without averaging would require 255 µs. This signaling scheme would also enable the BER to be estimated from the pilot symbols present in each frame, therefore providing a more robust means of assessing performance than estimating SINR. Similarly, PER can be estimated by examining the packets after decoding.

The far-field pattern of the beamformer in beam-steering mode, as a function of azimuth angle φ, elevation angle θ (which is assumed to be 0°), phase weight β, and inter-element spacing d, is given by [8]

$$E_f(\theta,\varphi,\beta) = 1 + b e^{j2\pi \frac{d}{\lambda}\sin\phi\sin\theta + \beta}, \tag{1}$$

where b = -1 or 1 for null-steering and beamforming, respectively, $\lambda = c/f$ is the wavelength, f is the operating frequency, and $c = 3\text{x}10^8$ m/s is the speed of light in freespace. For the rest of our discussion, we consider propagation only in the horizontal plane, so that $\theta = 90°$.

III. Beamformer Performance

In this section, (1) is evaluated over the UWB operating band and the resulting array pattern is analyzed when operating in beam- and null-steering modes. With reference to (1), β is assigned a quantized phase shift according to the 3-bit quantizer, $\varphi = [-\pi, \pi]$ rad, and λ

assumes values corresponding to the UWB frequency band. The performance is first investigated in terms of beam-steering, followed by the null-steering performance. The locations and widths of the beams and nulls are investigated as functions of frequency.

A. Beam-Steering

With reference to Fig. 2, the $\pi/4$ radian step size enables the main beam to be steered in steps of approximately 8°. A 3 dB beamwidth of approximately 35° is measured at the center frequency, while the 10 dB beamwidth is approximately 60°. Fig. 2 has been plotted using (1) with the relevant parameters inserted and for each value of phase shift. The beam patterns shown in Fig. 2 is obtained at f_c = 6.85 GHz. As the radiation pattern of the array is symmetric about the array axis, the beam pattern is shown for $-\pi/2 \le \varphi \le \pi/2$ rad. An identical pattern is obtained in the other hemisphere. The null-to-null beamwidth is given in degrees as $\Delta\varphi = 70\,\lambda/D$. Here λ is the wavelength, $D = (N-1)d$ is the aperture of the uniform linear array, and N = 2 is the number of antenna elements. The variation of the null-to-null beamwidth within the UWB bandwidth is quantified in Fig. 3, showing that $\Delta\varphi$ ranges from 50° at 10.6 GHz to 170° at 3.1 GHz. Even though this variation appears to be large, it should be taken into account that the boresight mainlobe direction is independent of frequency due to the use of a frequency invariant phase shifter, with the consequence that the beam converges for all frequency components. Fig. 4 illustrates this point using 500 MHz wide signals, such as those used in MB-OFDM, centered at various frequencies within the FCC UWB band, when the beamformer phase weight is 0°. For each operating frequency, the azimuthal wideband power is computed as

$$P(\varphi,\beta) = \sum_{f=f_l}^{f_h} \left| E_f\left(\theta = \frac{\pi}{2}, \varphi, \beta\right) \right|^2, \tag{2}$$

which corresponds to power integration over the signal bandwidth. While considerable variation in the beamwidth is noticed, the beam directions for all center frequencies coincide at 0° as intended. Next, to analyze the impact of signal bandwidth on the performance of the beamformer, the beam pattern is plotted in Fig. 5 for signals ranging from a single sinusoid to one containing the full spectral content of the FCC UWB band, where each signal is centered at 6.85 GHz. It is seen that the bandwidth has little impact on the beamwidth or direction, and the beam focusing capability will therefore not be sensitive to the signal bandwidth used. These observations demonstrate that the proposed beamformer can be useful for UWB systems and does not suffer performance degradation due to the large signal bandwidth.

A. Null-Steering

This step size (π/4 rad.) enables the null to be steered in approximately 12° steps. When the 3 dB null width is approximately 25° measured at the centre frequency of operation, i.e. f_c = 6.85 GHz, approximately 12° of overlap between adjacent nulls is observed, as shown in Fig. 6. Note that the mapping from phase setting to null location is nonlinear, and hence the null spacing is also nonlinear as shown in the figure. The methodology used for producing this figure is the same as that used for producing Fig. 2, with the exception of switching the beamformer to null-steering mode. Figure 7 shows the null pattern of 500 MHz wide signals at various centre frequencies in the UWB band, and it is observed that the nulls coincide at the desired location, 0° when the phase weight is 0°, irrespective of the frequency of operation.

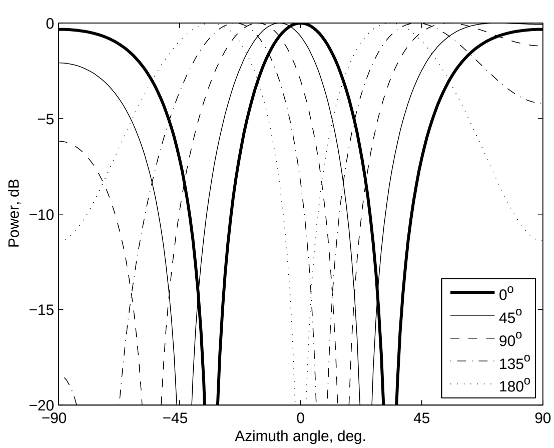

Fig. 2. Main beam location with a three-bit quantized phase shifter at f_c = 6.85 GHz and the specified β.

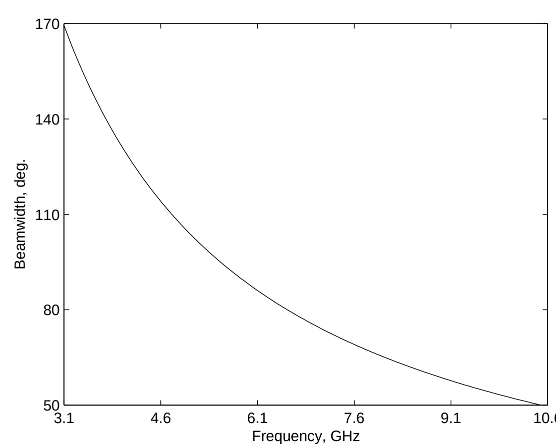

Fig. 3. The variation of beamwidth with frequency in the UWB band.

C. Range Extension

When operating in the beam-steering mode, the two-element array doubles the field strength, which translates to a directive gain of 3 dBi [14]. Assuming that the receiver beam is directed towards the dominant incoming signal component, we can therefore expect a gain of 3 dB in the received signal power and SNR. The impact of this SNR improvement, $\Delta\rho$ dB, on the coverage range can be evaluated as [1]

$$\Delta r = r_0\left(10^{\Delta\rho/10n} - 1\right), \tag{3}$$

where Δr is the range extension beyond the original range r_0, and n is the pathloss index. For an indoor LOS UWB channel, n = 1.7 [15]. Therefore, from (3), $\Delta r \approx r_0/2$, i.e., the proposed beamformer provides a 50% range extension on average. Thus, if the original operating range of the single-antenna UWB system was 10 m, the range achieved due to the beamformer is nearly 15 m.

D. Interference Rejection

The degree of interference suppression achieved depends on the angular spread of the interfering signal, its relative power, and the operating mark of the beamformer. In an indoor propagation scenario, a single signal source will be spread in angle due to reflections. The degree of angular spread depends upon the signal's Ricean K-factor, where a high K-factor corresponds to little scattered energy (line-of-sight), while a low value corresponds to most of the energy being scattered (non-line-of-sight). Angular spreads in the 20°–100° range are often considered in indoor environments when operating in the 5 GHz band, depending on the amount of clutter and scattering [16]. Furthermore, with multiple interference sources, the degree of angular spread will be increased further. With a two-element array operating in null-steering mode, we can expect a signal null to be steered at a single dominating interferer. The beamformer proposed in this paper will achieve this regardless of the frequency of the interfering signals.

Angular spreads with a Laplacian distribution and a standard deviation of 38° can be expected in indoor UWB channels, with 1-2 clusters [17]. Thus, from the earlier analysis, we can expect the interferer to be suppressed by at least 3 dB, providing a 3 dB SINR improvement.

Interference suppression is also possible in beamforming mode, where this is limited by the sidelobe levels. The advantage is that suppression occurs for a wider range of angles and is not limited to the null width.

IV. Discussion and Conclusions

This paper has described a simple beamformer for UWB wireless networks. The beamformer has been shown to steer either a beam or a null that retains a constant steering angle over the UWB bandwidth. An adaptation process is described that does not require a complex adaptive algorithm, but instead switches through a sequence of configurations, where the configuration giving the best performance is subsequently selected.

Such a beamformer is able to steer a single beam or null, thus a single signal can be targeted. If the angular spread of this signal is grater than the beam (or null) width, the performance will be sub-optimal. Also, sub-optimal performance will result if there are multiple signals of similar power from multiple azimuth angles.

The limitation caused by multiple signals impinging on the array can be addressed by increasing the beamformer complexity, i.e., increasing the number of elements and/or having multiple beamformers. This is clearly not viable for consumer electronic applications. Note also that, to the best of the authors' knowledge, the dynamic characteristics of such signals are not currently available in the open literature. Characterizing these signals is a

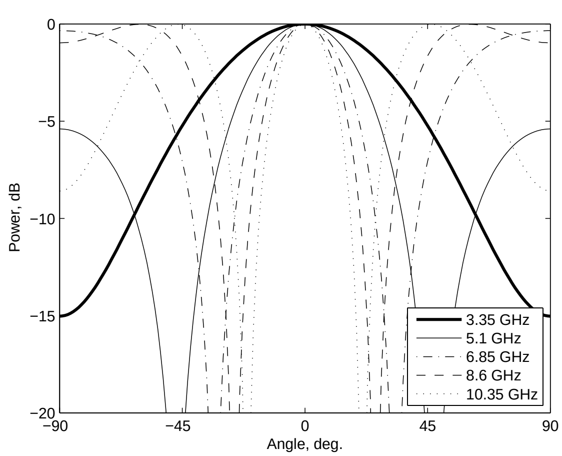

Fig. 4. The variation of beam pattern with center frequency when a 500 MHz wide signal is used.

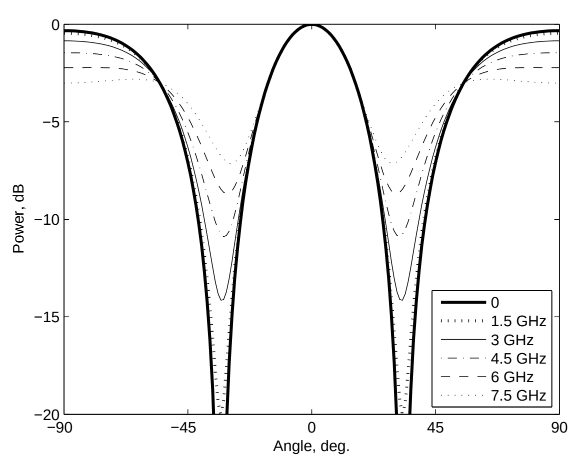

Fig. 5. The effect of bandwidth on the beam pattern at f_c = 6.85 GHz.

topic for further research. The research reported here has assumed a single dominant wanted or interfering signal or cluster of signals. As well as spatial filtering, the beamformer has also been shown to provide a range extension of 50%. Thus, without any additional transmit power and without any significant channel estimation and signal processing complexity, the maximum operating range can be extended from 10 m to 15 m.

ACKNOWLEDGEMENT

This work was supported by the UK Engineering and Physical Sciences Research Council under Grant GR/T21769/01.

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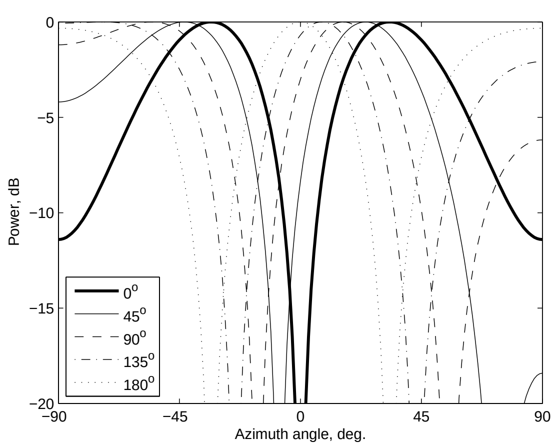

Fig. 6. Null locations with a three-bit quantized phase-shifter at f_c = 6.85 GHz.

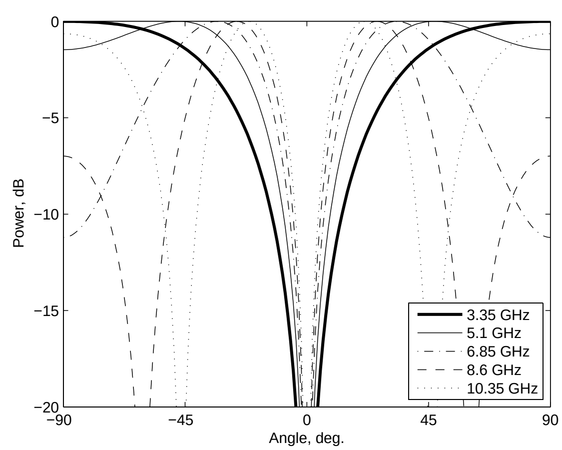

Fig. 7. The variation of null pattern with center frequency when a 500 MHz wide signal is used.