Mechanical Steerable Lens for Wireless Communications

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Abstract: This paper presents a new concept of a steerable beam antenna, where a dielectric lens antenna is tilting and/or rotating in front of a stationary feed. In this way, the beam is mechanically scanned in elevation and azimuth. The dielectric lens is properly shaped and positioned accordingly with two requirements: high gain and beam steering capacity. The arrangement is very simple, it requires no rotary joints and it represents a compact and low-cost solution. The focus is placed on providing a beam steerable antenna for millimetre wave communication systems, more specifically for Wireless HD, being the concept applicable for different services. The fabricated prototype adopts a circular horn antenna with moderate gain as the feed (13 dBi). The shaped dielectric lens allows beam steering while also increasing the entire structure gain to 21dBi. The mechanical steerable beam antenna presents a broadband behaviour, including the entire international unlicensed spectrum from \( f = 57 \text{ GHz} \) to \( f = 66 \text{ GHz} \). The antenna is able of tilting the beam from \(-45^\circ\) to \(45^\circ\) for all azimuths with gain scan loss below 1.1 dB and radiation efficiency above 95%. The entire antenna structure volume is around \(3\times3\times3 \text{ cm}^3\), with the lens weighting just 8 g.

I. INTRODUCTION

A new wireless communication system is being developed, Wireless HD, as an initiative of several leading technology and consumer companies in order to create an industry standard that will define the next generation of wireless systems related with consumer electronics [1]. The system is intended to use the unlicensed spectrum from 57 GHz to 66 GHz. At these frequencies, atmospheric attenuation is very high, due to oxygen absorption (it causes a 15 to 30 dB/Km loss [2]), being more suited for home entertainment, with radio links distances smaller than 10 m, as presented in Figure 1. Wireless HD sets itself apart from other wireless standards because it can transmit high definition video streams without the need for compression. The target of the Wireless HD high-speed radio communication standard for data rates of up to 4Gbps is defined as handling full HD (1080p) video without high-efficiency coding [1].

The free space attenuation in the available frequencies band is of extreme relevance when considering a communication link with 10 m length. In order to surpass this difficulty, high gain antennas are required to improve the connection link and ensure acceptable system performance and range as well as prevent multipath interference. As a result of a narrower beam, steerable beam capability is mandatory to automatically point the main beam into the transmitting device direction. In the past few years several solutions were presented for steerable antennas, including electronically and mechanical scanning antennas.

The Wireless HD standard specifications are briefly listed in Table 1. The designed antenna must present full azimuth scan, a beam tilt of \(\pm40^\circ\) with gain beam steering loss lower than 2 dB and beam efficiency above 95 %. The antenna is also required to be compact and adequate for low cost mass production.

| Table 1 – Millimetre-Wave Communication System Specifications (Wireless HD) |
|---------------------------|-----------------|-----------------|
| Frequency spectrum [GHz]        | 57 - 66         | Wireless HD    |
| Antenna Gain [dBi]              | 20              |                |
| Elevation Scanning Width [°]    | \(\pm40\)       |                |

The adopted antenna solution corresponds to a mechanically steering antenna, due to its low cost and overall efficient performance. There are two main possibilities when considering mechanical steering antennas: reflectors and dielectric lenses. Due to size restrictions, an axial symmetric dielectric lens with a single material
was adopted (a more compact solution). Axial symmetric lenses were selected instead of a 3D optimized lens because the design and fabrication process is much simpler.

II. CONCEPT DESCRIPTION

Regarding the antenna requirements and its structure previously described, the designed lens must be able to increase the overall gain and further steer the beam when pivoting in front of the fixed feed. The two specified desired targets can be achieved by appropriately shaping both lens surfaces. When considering high gain lenses, the best solution is a collimated lens with a reasonably large surface, since it focuses the feed radiation into a specific direction, increasing the beam directivity. In order to obtain a steerable beam antenna, two possibilities were considered: tilting the lens in a way that the feed phase centre always relies on the lens focal arc; tilting the lens about its central focal point. In the first approach, the lens corresponds to a collimated lens with a scanning condition while for the second one, the absence of the scanning condition allows one to optimize the lens profile concerning the beam steering performance. Both configurations allow azimuth scanning by rotating the tilted lens in relation to the feed axis, being able to produce a beam tilt of 360º.

III. LENS TILTED ACCORDINGLY WITH ITS FOCAL ARC

The typical solution for beam steering lens antennas (scanning lens) [4] consists on having an array of sensors distributed along the lens focal arc, where each array element corresponds to a specific radiation direction, θlsb, see Figure 2. The proposed alternative corresponds to have a single sensor, or feed, placed at the lens focal point and tilt the lens accordingly with its focal arc. The lens is tilted in a way that its phase centre always falls along the focal arc trajectory, coincidently with the static feed position; see Figure 3, where θbeam represents the beam tilt angle in relation to the feed axis, θlens is the lens tilted angle (corresponds to the θlsb symmetric angle in Figure 2) and θlsb is the beam tilt angle in relation to the lens axis.

![Figure 3 - Lens tilted accordingly with its focal arc.](image)

a. MODIFIED ABBE LENS

A simple and common method to design a scanning lens is the Abbe sine condition formulation [5]. The Abbe sine condition is satisfied when the intersection points of the extended rays departing from the on-axis sensor and the corresponding extended transmitted rays all lay on a circumference centred at the sensor [5]-[6]. The Abbe sine lens geometry is presented in Figure 4, with its height given by F and T, focus distance and lens thickness, respectively. The inner lens shell is defined by r (θ) while the outer shell is represented by the length l (θ) and the angle γ (θ). The Abbe sine condition corresponds to make intersect the extended rays r (θ) departing from the source and the corresponding extended transmitted rays s (θ) on a circumference centred at the source, with radius f, green colour circumference in Figure 4. A detailed description of the Abbe sine lens is made in [6]. To increase the lens aperture size when designing an Abbe sine lens, the Abbe sine condition was modified in such a way that the rays’ intersection curve could have other shapes instead of a circumference; however, the scanning effect is slightly affected, with an
increased comma aberration. The circumference curve was replaced by $f_e(\theta) = f_{e0} - \Delta f_e \cos(Q\theta)$, where $f_{e0}$, $\Delta f_e$ and $Q$ are free parameters to be optimized.

![Figure 4 – Abbe sine lens.](image)

The polyethylene material ($\varepsilon_r = 2.35$, $\tan \delta = 0.0004$) was selected for lens fabrication because of its low loss tangent, favouring high radiation efficiency. The projected lens dimensions are defined by a lens diameter equal to 30 mm, a focal distance of $F = 12.5$ mm and a lens thickness of $T = 12.5$ mm. The parameters values that define the intersection curve for the Abbe sine condition correspond to $f_{e0} = 19.5$ mm, $\Delta f_e = 0.425$ mm and $Q = 1.06$. The intersection curve is closely approximated by a circumference of radius 19.075 mm; however, by slightly lifting the curve, a higher angle of incident rays is allowed, leading to wider scan angles and better efficiency. Figure 5 and Figure 6 show the ray tracing analysis considering on-axis and off-axis feed positions, along the lens focal arc. The maximum feed offset of the lens corresponds to a maximum scanning angle of $\theta_{bl} = 24^\circ$ for a lens tilt equal to $\theta_{lens} = -72^\circ$, corresponding to a beam tilt of $\theta_{beam} = -48^\circ$ when considering the feed axis. When tilting the lens accordingly with its lens focal arc, the feed illumination of the lens decreases, favoring high spillover. The relation between the lens and the beam tilt is approximately close to $\theta_{beam} = 0.63 \theta_{lens}$, representing a relevant discrepancy, which allied to the lens spillover, strongly limits the antenna maximum beam steering angle.

![Figure 5 – Lens ray tracing for on-axis feed position (ILASH).](image)

![Figure 6 – Lens ray tracing for maximum feed offset position (ILASH).](image)

**b. Circular Horn Feed**

Lens and horn antennas dimensions were carefully obtained considering a compromise between a reasonably small size of the overall structure and the intended gain of the antenna. A circular horn antenna with moderate gain was designed in order to efficiently illuminate the lens with low spillover. For this purpose a circular horn antenna with a full beam width of about 70º at -10 dB and circular polarization was adopted. Circular polarization was used in order to minimize polarization mismatch that can occur in line-of-sight links with linear polarization portable equipment (if the portable device is tilted by 90º there would be a polarization mismatch between the source and the receptor). The horn was manufactured in aluminium with 7.8 mm inner aperture diameter, 10 mm flared length and 3.9 mm diameter circular waveguide port, Figure 7. The horn is fed in the TE$_{11}$ mode with right-hand circular polarization.
Figure 7 – Circular horn feed, manufactured prototype.

The measured radiation pattern of the standalone circular horn at $f = 62.5$ GHz is represented in Figure 8, superimposed on the CST simulations. A general good agreement is shown between measurements and simulations, both for co- and cross-polarization. The measured gain is 13.6 dBi, while the input reflection coefficient $|s_{11}|$ is always below -20 dB for both cases.

![Figure 8 – Circular horn feed, measured and simulated radiation pattern.](image)

**c. Antenna Simulations**

In Figure 9 is presented the far field radiation pattern for several tilted angles of the lens at $f = 62.5$ GHz. It is shown that in order to achieve a high beam tilt angle, the lens must tilt a wide angle over the focal arc centre, leading to high scan loss, since the horn antenna is no longer illuminating the lens efficiently. It is seen that by tilting the lens, a second lobe gains relevance on the direction of the feed main beam.

![Figure 9 – CST simulated radiation pattern at $f = 62.5$ GHz with the lens tilted from 0º to -72º.](image)

Considering the directivity variation with the lens tilt angle and the 2 dB margin established as the gain scanning loss limit, the interval where this lens configuration suits the Wireless HD standard is inferior to $\theta_{beam} = \pm 30^\circ$ of beam tilt; besides, the side lobe level for a beam tilt of this amplitude presents about -12 dB, which can be considered relatively high.

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Table 2 – Modified Abbe lens performance parameters

IV. Lens Tilted in Relation to its Phase Centre

The main goal of this antenna configuration is to obtain a steerable lens that is able to focus accordingly with the direction of the lens, which means that the radiated beam follows the lens axis. Collimating lenses focus all incident rays along the lens axis direction, when the feed is placed at the lens phase centre; considering this, by tilting the lens in relation to its phase centre, the rays immersing from the lens are still parallel to the lens axis, focusing the beam into the desired direction. In Figure 10 is shown the lens tilt configuration.

![Figure 10 – Lens tilted in relation to its phase centre.](image)

Two lens geometries are presented: a first one based on a single refraction surface, which allows understanding the concept configuration and a second one, a double refraction lens, optimized in order to maximize the beam steering angle. For simplicity the designed lenses are onward referenced also as L1 and L2.
a. **Single Refraction Surface Lens**

An elliptical lens is a common example of a focusing lens [7]. With the feed integrated at the lens base, placed at the ellipse focal point, by tilting the lens accordingly with the feed phase centre position, Figure 11, the rays exit parallel to the lens axis, showing an almost exact correspondence between the lens tilt $\theta_{\text{lens}}$ and the beam tilt $\theta_{\text{beam}}$. The feed is integrated inside the lens or at the lens base and so, in order to allow the lens movement, remaining the horn fixed, the solution used consists on the same approach adopted for a LEO satellite application in [8]. The proposed configuration corresponds to open a spherical air dome concentric with the ellipse focal point to allow the lens to be tilted and rotated without impairment from the feed, as seen in Figure 11. The dome spherical shape eliminates refraction at the inner interface of the lens and thus no significant change is produced on the lens’s outer surface illumination by the feed and consequently no relevant modification appears in the lens far field radiation pattern.

![Figure 11 – Elliptical dome lens ray tracing.](image)

The lens collimating region, based upon Geometrical Optics, is defined by the maximum incidence angle of the feed:

$$\theta_{\text{max}} = \arccos \left( \frac{1}{n_\varepsilon} \right) = 49.3^\circ$$  \hspace{1cm} (1)

where $\varepsilon$ is the lens material permittivity. The proposed antenna was designed with the in-house developed software tool (ILASH [9] - [11]), which makes use of the hybrid Geometric Optics + Physical Optics lens analysis method. Further lens evaluation was made considering a full wave analysis with CST Microwave Studio™.

The ellipse main axis presents radius of 13.18 mm and 10 mm, corresponding to a base radius of 10 mm and a lens height of 21.8 mm. The manufactured prototype, along with the lens tilting set-up is presented in Figure 12.

![Figure 12 – Elliptical dome lens (L1), manufactured lens plus horn feed.](image)

The software application [12] that controls the measurement process, data acquisition, manipulation and visualization at the millimetre wave anechoic chamber in Instituto de Telecomunicações was improved in terms of its structure and organization, making it more flexible and easier to use. Its user-friendly interface suffered some changes; however, the most important addition was the inclusion of two positioners, which highly improved the measuring performance.

The antenna was evaluated at $f = 62.5$ GHz, slightly close to the central frequency of the Wireless HD spectrum. The radiation pattern measurements, presented in Figure 13, show a good agreement with CST simulations. The lens was tilted between non-tilted position and $\theta_{\text{lens}} = -40^\circ$, with steps of $10^\circ$. For non-tilted position the antenna presents a gain of 21.6 dBi. The mechanical steerable beam antenna is able of tilting the beam from $-40^\circ$ to $+40^\circ$ by $360^\circ$ in azimuth without hitting the horn feed. Simulations demonstrated the lens broadband behaviour, including the entire Wireless HD standard spectrum.

![Figure 13 - Measured and simulated radiation patterns of the L1 lens antenna for $\theta_{\text{lens}} = 0^\circ$ to $-40^\circ$.](image)
The main beam direction ($\theta_{\text{beam}}$), presents an increasing difference in relation to the lens tilt angle ($\theta_{\text{tilt}}$), because, as the lens tilts, the feed illumination gradually exceeds the $\theta_{\text{max}}$ angle, exiting the lens collimating region. By doing so, part of the feed radiation starts to build side lobes and a lateral wave is launched along the lens outer interface, diminishing the maximum scanning angle to near 25º if considering a 2 dB scan loss gain as the limit. The radiation efficiency is always above 96%.

Table 3 - Measured performance of the L1 lens. $\Delta G$ is the gain scan loss, XPol is the higher cross polarization level in the main beam full width at -10 dB and $\eta$ is the CST simulated radiation efficiency.

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<th>$\theta_{\text{beam}}$ [°]</th>
<th>$G$ [dB]</th>
<th>$\Delta G$ [dB]</th>
<th>XPol</th>
<th>$\eta$ (%)</th>
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b. DOUBLE REFRACTION SURFACES LENS

The objective of having a two refraction surfaces lens is that a second degree of freedom will allow a maximization of the portion of the lens surface that is able to collimate the feed’s radiation, increasing the lens $\theta_{\text{max}}$ angle of incidence, see Figure 14.

Figure 14 – Two refraction surfaces lens geometry.

The inner surface, $r(\theta)$, is defined analytically using a Taylor series expansion in order to the angle formed by the ray path departing from the feed ($\theta$):

$$r(\theta) = \sum_{n=0}^{8} C_n \theta^n$$  \hspace{1cm} (2)

where $C_0 = F$, $C_1 = 0$ and $C_{2...8}$ are the coefficients to optimize. $C_1$ is null in order to impose $\partial r/\partial \theta = 0$ at $\theta = 0º$ and so ensuring null refraction for the central ray. The outer shell can be defined by the angle $\gamma(\theta)$ and the length of the rays $l(\theta)$. Using the Snell law condition at the inner shell interface leads to:

$$\frac{\partial r(\theta)}{\partial \theta} = \frac{\sqrt{\varepsilon_r \sin[\theta - \gamma(\theta)]}}{\sqrt{\varepsilon_r \cos[\theta - \gamma(\theta)]}} l(\theta)$$  \hspace{1cm} (3)

By imposing an electrical path length condition we get:

$$F + \sqrt{\varepsilon_r} T = r(\theta) + \sqrt{\varepsilon_r} l(\theta) + s(\theta)$$  \hspace{1cm} (4)

with

$$s(\theta) = F + T - r(\theta) \cos(\theta) - l(\theta) \cos[\gamma(\theta)]$$  \hspace{1cm} (5)

Since the inner shell profile is analytically defined by (2), the differential equation (3) can also be determined analytically. $F$ and $T$ are input constants, defining the lens height, whereas $r(\theta)$ and $\gamma(\theta)$ are unknown functions. The optimization method consists on using the genetic algorithms (GA) formulation, where the $C_{2...8}$ coefficients are generated as individuals on a larger population where a set of $C_n$ parameters corresponds to a unique solution of a lens. Setting the $C_n$ coefficients defines the $r(\theta)$ function in (2) so $\gamma(\theta)$ is calculated from (3) and then $l(\theta)$ is obtained from (4) and (5). With $r(\theta)$, $\gamma(\theta)$ and $l(\theta)$ the upper surface is defined. The above formulation is integrated on a GA optimization loop, generating and testing different lenses’ shapes, with the goal of maximizing $\theta_{\text{max}}$, as mentioned before. Two constraints had to be added:

- $r(\theta) > 4.5$ mm, to ensure that the horn edges never touch the lens surface when this is tilted;
- ray incidence angle at the upper lens interface must be below 95% of the critical angle.

The last constraint is included in order to minimize the excitation of a lateral wave along the lens upper surface that tends to deflect part of the lens radiation away from the main beam direction reducing the directivity. This occurs when ray’s incidence angles approach the total reflection condition (presented angle corresponds to the polyethylene material):

$$\theta \geq \theta_c = \arcsin \left( \frac{1}{\sqrt{\varepsilon_r}} \right) = 40.7º$$  \hspace{1cm} (6)
The lens was designed with $F = 5$ mm and $T = 20$ mm to obtain a lens with similar size as the elliptical one and identical directivity. The optimization process lead to:

$$r(\theta) = 0.0274\theta^8 + 0.7683\theta^7 + 0.4522\theta^6 + 0.2553\theta^5 + 0.3774\theta^4 + 0.7369\theta^3 + 0.7353\theta^2 + 5$$

(7)

The second lens, called L2, was manufactured and placed at the lab test set-up the same way as L1, Figure 15. It weights 8 g, slightly larger than the previous one. In this case the lens tilting axis lies outside the lens volume, so two lateral extensions of the same material had to be added to provide fixing points for lens tilting. The presence of these extensions hardly affects the lens radiation pattern because they are not illuminated by the horn main lobe.

The measured radiation pattern of the L2 lens, for $f = 62.5$ GHz, is shown in Figure 16. Both co- and cross-polarization radiation patterns are presented for lens tilt angles from $\theta_{\text{lens}} = 0^\circ$ to $\theta_{\text{lens}} = 50^\circ$, with steps of $10^\circ$. The improvement from the elliptical lens is quite remarkable. The L2 lens presents considerable lower scanning loss gain than the L1 lens and also presents a much better defined main beam up to the maximum beam steering angle of $45^\circ$. The marginal beam deformation with tilt angle is not critical for the Wireless HD application.

![Figure 15 – Two refraction surfaces lens (L2), manufactured prototype.](image)

Table 4 - Measured performance of the L2 lens. $\Delta G$ is the gain scan loss, $XPol$ is the higher cross polarization level in the main beam full width at -10 dB and $\eta$ is the CST simulated radiation efficiency.

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V. Conclusions

A new steerable beam antenna concept was developed and proved against Wireless HD requirements, being the same design principles valid for similar applications. The presented solution, making use of a collimating lens, corresponds to a totally new scanning concept, although collimating lenses are widely used for scanning purposes. The beam steering is obtained by pivoting an appropriately shaped dielectric lens in front of a single fixed feed, instead of the regular matrix of feeds at the base of a fixed lens. The proposed mechanical beam steering antenna is simple, compact and it represents a low-cost solution for large scale production.
When considering the optimization of a double refraction surfaces lens, the lens performance greatly improves when comparing it to an elliptical lens, highly due to the extra degree of freedom used in the optimization. The fabricated mechanical steerable lens prototype fully comply with the Wireless HD requirements, demonstrating a ±45º elevation scan capability over full azimuth with gain scan loss lower than 1.1 dB and radiation efficiency above 95% for the entire spectrum of the referred standard (from $f = 57$ GHz to $f = 66$ GHz). The lens weights only 8 g, which for mechanical steering is a critical quality.

In order to adjust the presented lens antenna to a different application, higher beam tilt angles can be achieved by using materials with higher permittivity. For different operating frequencies and associated gains a scaling of the complete solution would almost be enough to comply with different requirements.

**VI. References**


