A Microstrip Quasi-Yagi Antenna based on Optimised Waning Crescent Elements for WSN

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Abstract

In this paper, a novel microstrip Quasi-Yagi antenna based on Waning Crescent elements, is presented. The proposed antenna employs a microstrip dipole as the radiating element and, optimised waning crescent shaped elements as reflector and directors. The antenna is designed and optimised to operate in the 2.4 GHz ISM band, attending the integration in a multi-sector base station antenna configuration for a Wireless Sensing Network (WSN) for environmental monitoring. In particular, specific project requirements, such as: resonating frequency, gain, half power beam-width (HPBW) are taken into consideration when dimensioning the antenna. Simulation results ensure a realized gain of 9.4 dBi, a HPBW of 63° and a back-to-front ratio of 20.2 dB, at a resonating frequency of 2.45 GHz.

1 Introduction

Wireless Sensor Networks (WSNs) are often presented in the literature as a solution for large-scale autonomous monitoring systems [2]. These networks have surged from the need of cooperative monitoring solutions, to monitor physical parameters, as *e.g.* humidity, temperature, pressure, *etc.*, for target applications such as: environment monitoring [3], security [4], health monitoring [5], agricultural [6], hazard detection [7], among many others.

In particular, WSN are composed by multiple Sensor Nodes (SN) scattered in a area of interest and, a Base Station (BS). While the SN collect physical parameters of the nearby environment, the BS collects and compiles the data from all nodes. In the majority of WSN environmental applications, it is desirable to have a BS capable of covering its surroundings, and thus omnidirectional coverage is often required. However, antennas with such radiation pattern generally offer relatively low gain, limiting the overall dynamic range of the system [8].

Techniques such as sectorization [8], can be employed in order to increase on the overall BS gain, while providing a 360° Field of View (FOV). In particular, antenna sectorization technique divide the BS coverage area into sectors so that higher directivity antennas, with lower FOVs, can be employed. This technique can be easily applied with directive antennas and a multiplexing feeding mechanism [1](*e.g.* RF Switch), instead of large antenna arrays and more complex feeding network, as often required in other techniques, such as beamsteering or beamforming [8].

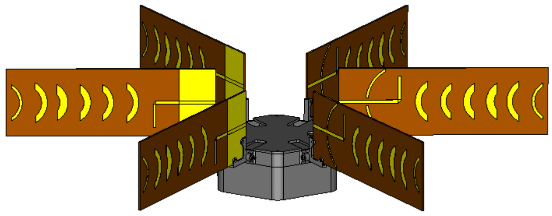


Figure 1. Example of multi-sector WSN base-station antenna configuration.

Several examples of antennas elements for BS can be found in the literature. In [9], the authors presented the study and optimization for a directive wideband Vivaldi antenna, with dual-polarization, for 5G base-stations. Meanwhile, in [10] it is proposed an 1×4 array of an enhanced inverted-F shape antenna, to be deployed in a Wi-Fi base station. The authors in [11] suggested a different approach for a BS antenna, by developing a broadband solar radiating element which comprises 4 solar cells that act like a radiation aperture. Finally, in [12] a filtering antenna was design specifically for a BS operating in the 2.4 GHz ISM. The filter is used for improving the isolation between adjacent BS elements while ensuring the stability of the overall radiation pattern of the BS.

In this paper, a new microstrip Quasi-Yagi antenna design, based on waning crescent shaped directors and reflector, is presented. The antenna is designed to fulfil specific project requirement, such as: resonating frequency, gain, half power beam-width (HPBW), and ultimately, to be deployed in multi-sector BS antenna of a WSN network, as depicted in Fig. 1. Design guideline and simulation workout, followed by a thorough antenna optimisation is presented for an antenna operating in 2.4 GHz band, aiming at least 9 dBi of gain and a FOV of 60°, and a back-to-front ratio of at least 20 dB.

This paper is organised as follows: in Section 2 the antenna layout is thoroughly described. Section 3 presents a thorough parametric simulation and subsequent optimisation of the proposed antenna, using CST Microwave Studio. Finally, in Section 4 the main conclusions are drawn.

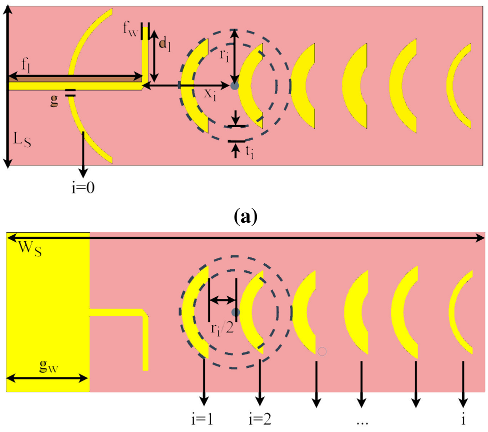


Figure 2. (a) Top view and (b) bottom view of the proposed waning crescent Quasi-Yagi antenna.

2 Antenna Layout

The presented antenna layout, depicted in Fig. 2, follows a microstrip Quasi-Yagi configuration. Etched parasitic elements with a waning crescent shape are considered as directors and reflector. The antenna is then composed of a microstrip dipole as driven element, a waning crescent reflector over a ground plane (defined by g_w) and, six optimised waning crescent directors. The waning crescent shaped directors follow the format ofa quarter of a circle centred at x_i, with radius (r_i) and thickness t_i, where $i = 0, 1, 2, \ldots$ represents the number of the of the reflector/director, as depicted in Fig. 2. The frequency of operation is defined by the dimensions of the dipole arms (dl), while the feeding line width (f_w) and length (fl) dictate the input impedance of the antenna. To avoid unnecessary signal reflection to the source, the 90° bend created by the disposition of the dipole arms and the feeding line was mitred, to reduce the capacitance of the line, maintaining the desired impedance. The antenna was designed in a double-sided FR4 substrate with $\varepsilon_r = 4.4$, a $tan\delta = 0.014$ and a thickness of $h = 1.6$ mm. The overall antenna dimensions are given by the parameters $W_S \times L_S$. The optimisation of the antenna dimensions and the number of directors are further analysed and discussed next section.

3 Design and Optimisation

This section describes the step-by-step design of the antenna with subsequent optimisation. The proposed antenna design configuration was dimensioned with the assist of a full wave electromagnetic solver (CST MWS), in an iterative design approach.

3.1 Feeding element

In a first iteration, the microstrip dipole with ground plane of Fig. 3a was designed and simulated, in order to study the length of the dipole arm needed to attain an antenna resonating of 2.45 GHz (target frequency). Therefore, a parametric study was carried out on d_l, with the initial value

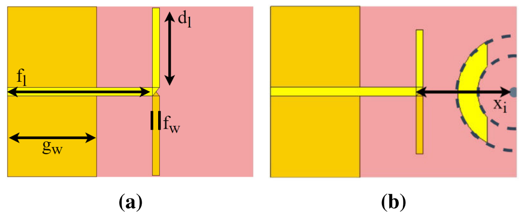


Figure 3. CST-MWS model of: (a) the microstrip dipole and (b) inclusion of a single director.

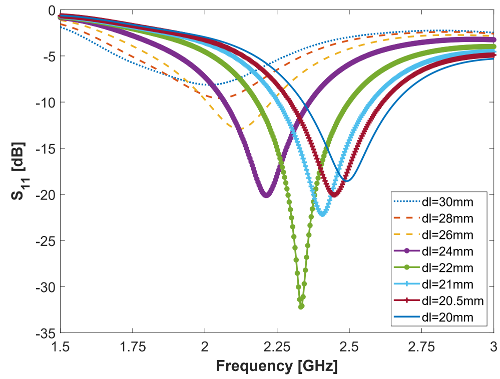


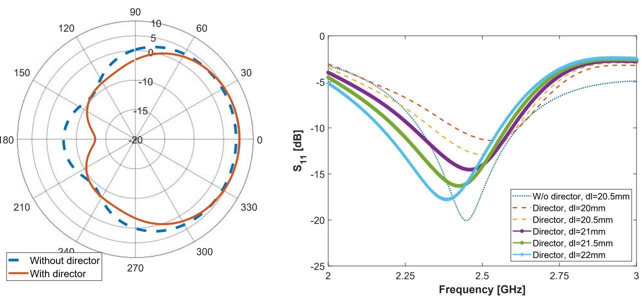
Figure 4. Simulated S_{11}-parameter for d_l variation.

being set at $\lambda_g/8$ and by fixing g_w at 32 mm, $L_S = 60$ mm and $f_l = 52$ mm. While L_S was defined to accommodate at least the arms length (i.e. $2\times\ \lambda_g/8$), f_l and g_w were deliberately defined to further accommodate the reflector shape. Additionally, f_w was set at 3.1 mm corresponding to a 50Ω impedance line for the proposed substrate. The simulation results of the parametric study are depicted in Fig. 4. The simulation ranged from 20 to 30 mm, with 0.5 mm step. From the simulation results, it is possible to observe that for $d_l = 20.5$ mm the antenna is resonating at 2.45 GHz.

3.2 Single waning crescent director

After optimising the dipole arms, the subsequent step in the antenna design is to evaluate the impact of adding the directors in antenna performance. Therefore, a single waning crescent director was added to the feeding antenna, at the position $x_1 = 32$ mm, as depicted in Fig. 3b. At this point, no reflector has been considered. The initial values of $t_1 = 8$ mm and $r_1 = 22$ mm where considered as starting point for the optimisation. The addition of the director caused two effects: an increase in the overall antenna gain and an undesirable deviation of the antenna's resonating frequency, as depicted in Fig. 5. While the first effect was expected (in line with the Yagi antenna concept [8]), the latter is associated with mutual coupling effects between the driven element and the added director. To further compensate for this frequency offset, the length of the dipole arms (d_l) were readjusted for 21.5 mm (Fig. 5b).

After re-tuning the antenna for the desired frequency, a parametric study was carried out in all parameters (r_1, x_1 and t_1) of the first waning crescent director ($i = 1$). The



(a) (b)

Figure 5. Impact of the addition of a single waning crescent director in (a) radiation pattern, at 2.45 GHz, and in (b) antenna S_{11}.

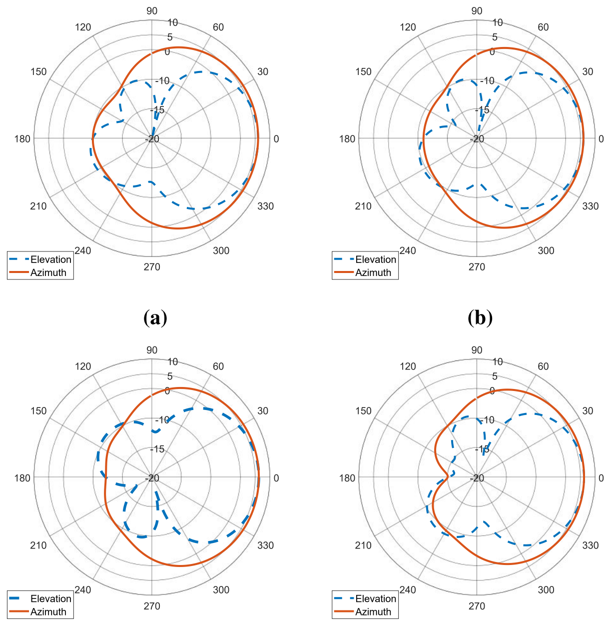
goal of the study is to optimise the director dimensions to achieve the best antenna gain possible. To this extend, the following methodology was been considered: a parametric simulation run for a single parameter at the time, while the others are assigned a fixed value. After discovering the value that would provide the highest gain, it becomes fixed, and a new parametric simulation on a different parameter is carried out. At the end of the study, this process is repeated once again, to ensure that the defined values are, in fact, the optimised ones (double confirmation).

In particular, Fig. 6 presents the radiation patterns obtained for different values of t_1, with x_1 and r_1 fixed at 32 mm and 22 mm, respectively. With $t_1 = 4$ mm the antenna presents a gain of 5.4 dBi (Fig. 6a), for $t_1 = 5$ mm the gain is of 5.5 dBi (Fig. 6b), for $t_1 = 6$ mm is 5.6 dBi (Fig. 6c), and finally, for $t_1 = 7$ mm the gain stabilises at 5.6 dBi (Fig. 6d).

In line with the methodology described above, further studies were carried out in the parameters x_1 and r_1, individually (not detailed in this publication due to paper length). From the final optimisation realised on the first director, it was found that the parameters which best favour the antenna performance in terms of gain are: $x_1 = 36$ mm, $t_1 = 5$ mm and $r_1 = 21$ mm, yielding a realised gain of 6.1 dBi. This results in an increase of 1.5 dB in gain, when comparing to the antenna without a director.

3.3 Antenna Gain vs. number of directors

An additional study was performed to access the gain improvement against the number of directors. The directors were added progressively to the layout, at the position $x_i = x_{i-1} + 20$ mm. Each director was further optimised for best antenna gain and impedance matching. Thus, it was ensured that all the parameters of each director (r_i, x_i and t_i) are optimised, individually, using de double confirmation technique described above, granting to the design the highest gain possible whilst keeping the $S_{11} < -30$ dB, in the resonance frequency. In particular, the maximum gain at the antenna boresight was obtained, and it is presented against the number of directors in Table. 1. From the results, it can be observed that after the addition of 6 directors, the ratio between gain and number of directors decreases. The difference from 6 to 8 directors is 0.6 dB, while the difference from 4 to 6 is 1.4 dB. Thus, for the best trade-off between antenna dimensions and gain, it was opted for 6 director's antenna which achieves the target gain 9.5 dBi. This represents an additional gain of approximately 3.5 dB, when comparing with the configuration of a single reflector.



(a) (b) (c) (d)

Figure 6. Radiation pattern on azimuth and elevation planes, at 2.45 GHz, for (a) t_1 = 4 mm, (b) t_1 = 5 mm, (b) t_1 = 6 mm and, (d) t_1 = 7 mm.

3.4 Waning crescent reflector

While taking in consideration the integration of the proposed antenna as an element of a multi-sector BS antenna, an additional waning crescent element was added as a reflector to the design. This has been performed with goal of improving the front-to-back ratio, and consequently, reduce the impact that the back-lobe radiation would have in adjacent antenna elements, if the circular configuration suggested in Fig. 1 is taken into consideration. The reflector was added prior to the feeding line (at the position x_0 = 6 mm), over the ground plane, and its dimensions were optimised using the same methodology previously described. From the parametric workout, it was found that the best front-to-back ratio is of 20.2 dB, obtained for $r_0 = 34.5$ mm, $x_0 = 6$ mm, $t_0 = 2.1$ mm and $r_d = 2$ mm, being improved in 5.7 dB when compared with the case without reflector (Fig. 7). However, with the values presented above, the HPBW of the antenna increases 3° and, consequently, the gain decays to 9.4 dBi.

Finally, after all the design optimisation in the proposed layout, an antenna with overall size of 185×60 mm^2, and dimensions of (in mm): $f_l = 52$, $g = 2$, $g_w = 32$, $d_l = 21.5$, $f_w = 3.1$, and director dimensions of: $x_0 = 6$, $r_0 = 34.5$, $t_0 = 2.1$, $t_1 = 5$, $r_1 = 21$, $x_1 = 36$, $t_2 = 5$, $r_2 = 19$, $x_2 = 56$,

Table 1. Simulated realised gain against the number of directors, without considering the reflector.

N. directors	0	1	2	3	4	5	6	7	8
Gain [dBi]	4.6	6.1	7.1	7.5	8.1	9	9.5	9.8	10.1

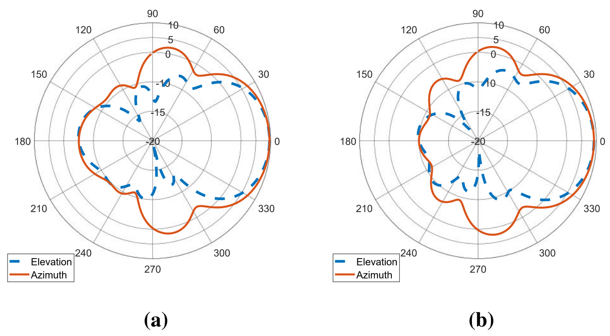


Figure 7. Radiation pattern in azimuth and elevation planes at 2.45 GHz, on the (a) without and (b) with the reflector.

$t_3 = 6$, $r_3 = 19$, $x_3 = 76$, $t_4 = 7$, $r_4 = 19$, $x_4 = 96$, $t_5 = 5$, $r_5 = 21$, $x_5 = 116$, $t_6 = 2.5$, $r_6 = 19$ and $x_6 = 136$, presents a realised gain of 9.4 dBi at 2.45 GHz, with a bandwidth of 450 MHz, a front-to-back ratio of 20.2 dB, and a HPBW of 63°. The final antenna radiation pattern can be seen in Fig. 7b.

4 Conclusions

A novel microstrip Quasi-Yagi antenna based on optimized Waning Crescent elements is proposed on this paper. The antenna, carefully designed and optimised to be implemented in a WSN BS, comprises a dipole acting as driven element, a waning crescent reflector and six optimised waning crescent directors. After a thorough set of parametric simulations and optimisation, an antenna designed in FR4 substrate, with overall dimensions of 185×60 mm^2, comprised of a single reflector and 6 directors, presents 9.4 dBi of realized gain, a HPBW of 63° and a back-to-front ratio of 20.2 dB, at a resonating frequency of 2.45 GHz. Further work will aim at antenna prototyping and experimental characterisation in laboratory environment, and subsequent implementation of a multi-sector base-station antenna (Fig. 1) for a wireless sensing network for environmental monitoring.

5 Acknowledgements

This research was partially supported by FCT under the project WSN-EM: PTDC/EEI-EEE/30539/2017 and by FCT/MCTES through national funds and when applicable, co-funded EU funds under the project UIDB/EEA/50008/2022.

References

[1] H. Asplund, D. Astely, P. von Butovitsch, T. Chapman, M. Frenne, F. Ghasemzadeh, M. Hagström, B. Hogan, G. Jöngren, J. Karlsson, F. Kronestedt, and E. Larsson, "Chapter 13 - Performance of Multi-antenna Features and Configurations," in *Advanced Antenna Systems for 5G Network Deployments*. Academic Press, 2020, pp. 561–637.

[2] S.-H. Yang, *Wireless Sensor Networks*. Springer London, 2014.

[3] B. Montrucchio, E. Giusto, M. G. Vakili, S. Quer, R. Ferrero, and C. Fornaro, "A Densely-Deployed, High Sampling Rate, Open-Source Air Pollution Monitoring WSN," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 12, pp. 15 786–15 799, dec 2020.

[4] S. Astapov, A. Riid, and J.-S. Preden, "Military Vehicle Acoustic Pattern Identification by Distributed Ground Sensors," in *2016 15th Biennial Baltic Electronics Conference (BEC)*. IEEE, oct 2016.

[5] G. Hernandez-Penaloza, A. Belmonte-Hernandez, M. Quintana, and F. Alvarez, "A Multi-Sensor Fusion Scheme to Increase Life Autonomy of Elderly People With Cognitive Problems," *IEEE Access*, vol. 6, pp. 12 775–12 789, 2018.

[6] D. Qiong and P. Hao, "Design and Implementation of Irrigation Water Saving Control System Based on WSN," in *2021 International Conference on Intelligent Transportation, Big Data & Smart City (ICITBS)*. IEEE, mar 2021.

[7] L. Shu, Y. Chen, Z. Sun, F. Tong, and M. Mukherjee, "Detecting the Dangerous Area of Toxic Gases with Wireless Sensor Networks," *IEEE Transactions on Emerging Topics in Computing*, vol. 8, no. 1, pp. 137–147, jan 2020.

[8] C. A. Balanis, *Antenna Theory: Analysis and Design, 3rd Edition*. John Wiley & Sons, 2005, vol. 72.

[9] P. Fernandez-Martinez, S. Martin-Anton, and D. Segovia-Vargas, "Design of a Wideband Vivaldi Antenna for 5G Base Stations," in *2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*. IEEE, jul 2019.

[10] P. Liu, J. Zhang, S. Lu, and J. Lin, "Design and Achievement of Miniaturization in Wi-Fi Base Station Antenna," in *Proceedings of 2014 3rd Asia-Pacific Conference on Antennas and Propagation*. IEEE, jul 2014.

[11] L. Hong, W. An, and S. Li, "A Broadband Solar Antenna Element for Base Station," in *2018 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC)*. IEEE, sep 2018.

[12] Y.-L. Chen and Q.-X. Chu, "A Novel Filter Antenna for Base Station," in *2019 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*. IEEE, sep 2019.