Plantenna

Plantenna: Using Plant Leaves to Increase Antenna Performance

Lieke A. M. Geubbels*, G. Federico*, V. Vidojkovic*, Jaume Anguera, IEEE Fellow§, Laurens A. Bronckers*
*Department of Electrical Engineering, Eindhoven University of Technology (TU/e), Eindhoven, the Netherlands,
[l.a.m.geubbels@student.tue.nl; g.federico@tue.nl; v.vidojkovic@tue.nl; l.a.bronckers@tue.nl]
§Ignion and GRITS remote-IoT research group at Universitat Ramon Llull, Barcelona, Spain,
[jaume.anguera@ignion.io; jaume.anguera@salle.url.edu]

***Abstract*—In agricultural applications, it is becoming ever more important to be able to send sensor data in an energy-efficient way, possibly from each plant. This study investigates the possibility to excite a plant leaf using an Antenna Booster to enhance antenna performance. A PCB including a Matching Network is designed to accommodate the Antenna Booster. This PCB is placed in a simulation environment on material emulating the electrical properties of a plant. It is shown that the Antenna Booster uses the PCB and the leaf it is placed upon to radiate. The simulations show that it is possible to increase the radiation efficiency of the antenna structure from 9.6% up to 15% at a frequency of approximately 2 GHz by attaching the Antenna Booster to a leaf-like plane, and that using the leaf thus should be considered in the Internet of Plants (IoP).**

***Index Terms*—Internet of Plants, Plantenna, Antenna Booster**

I. Introduction

THE Internet of Things (IoT) is a widely known concept nowadays. The main idea of IoT is empowering computers with means to gather their own data, and by doing so reducing, and eventually eliminating, the limitations of human-entered data [1], [2]. One of the main reasons why IoT is popular these days, is because of its many applications [3]. The IoT connects physical things, for instance plants, and lets them exchange information about themselves and their surroundings [4]. The concept of connected plants is also referred to as Internet of Plants (IoP). Even though the IoT is a popular concept, the antenna design in any IoT device remains a bottleneck [5]. [6] Describes the design of an IoT antenna and the difficulties, such as taking into account the total antenna efficiency and the sensitivity to the environment, in doing so. In particular, obtaining high efficiency for small antennas is a known challenge given the Chu-Harrington limit [7], [8].

A possible solution for IoP applications could be to use part of the plant itself as an antenna. Already in 1988, Chandraselar [9] published a study regarding the plantenna concept: plants are to be used as antennas. Chandraselar's study concerns special plants called hyper accumulators, which grow in soils with high metal concentrations and absorb these metals [10]. These hyper accumulators are being tested to observe any antenna like properties, but so far, this plantenna method has not yet proven to work [9].

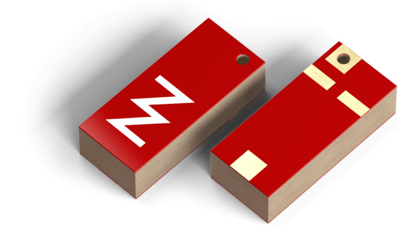


Fig. 1: DUO mXTEND Antenna Booster from Ignion with a size of $7\ \text{mm} \times 3\ \text{mm} \times 2\ \text{mm}$ [11].

This study focuses on using the plants in the IoP networks as plantennas. A plantenna could be used to increase the current crop yield and reducing resource waste by developing autonomous sensors which measure environmental and in-plant parameters. Subsequently, the plantenna will send this information to a receiver. The study does not continue upon the hyper accumulator study. Instead, it researches the possibility to excite a plant using the DUO mXTEND Antenna Booster shown in [11]–[13] and to increase the radiation efficiency of the radiating structure by simply adding a plant leaf. This Antenna Booster, as depicted in Fig. 1, is easy to implement and should therefore already propose a solution for the antenna design bottleneck. Therefore the main focus in this study is increasing the radiation efficiency by adding a plant leaf. This Antenna Booster can not be implemented directly onto the plant, since it needs a Matching Network (MN) to radiate. Therefore the Antenna Booster should be implemented on a PCB containing the MN. This general structure of the main idea of this research is illustrated in Fig. 2. This research covers the design of this PCB, as well as the simulation results using this PCB. This study includes multiple simulations using the Antenna Booster, performed with CST Studio Suite® [14] using the available encrypted model for the Antenna Booster.

The paper is structured as follows: Section II concerns the design process of the PCB, as well as the working principle of the Antenna Booster. Thereafter, the simulation results are given and elaborated in Section III. At last, the main conclusions are summarized in Section IV.

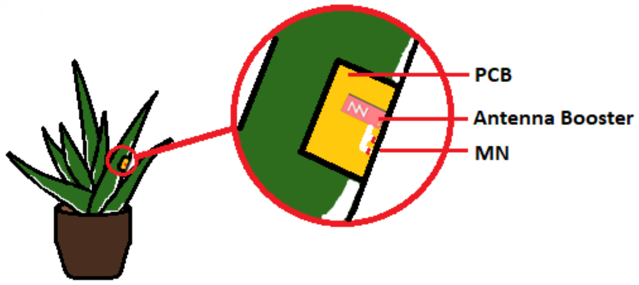
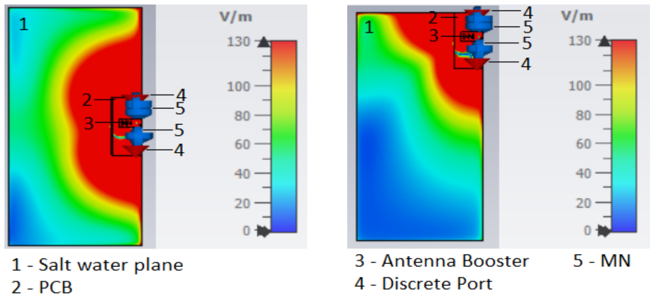


Fig. 2: General structure of the main idea of this research.



(a) (b)

Fig. 3: (a) The dipole-like E-field of the structure when the PCB is placed at the center edge of the salt water plane. (b) The monopole-like E-field of the structure when the PCB is placed at the corner of the salt water plane.

II. Design Process

This section firstly provides some insight in the working principle of the radiating structure, which underlies some of the design choices that are made. In addition, the design choices for the PCB are discussed. The parameters of interest are the working principle, the PCB dimensions and the design of the MN. These different parameters are researched using [15] before the final PCB was designed, and the knowledge obtained from these tests were applied when designing the final PCB.

A. Working Principle

When designing an antenna, a trade-off has to be made between the physical dimensions of the antenna and the antenna gain, efficiency, and bandwidth [7], [8], [16]. Smaller antenna dimensions often lead to a decrease in gain, efficiency and bandwidth. The Antenna Booster however, is up to 10 times smaller than other chip antennas while maintaining the same performance [17], [18].

As of yet, there is no study about the RF properties with directly applicable results of plants. This proposes an obstacle, since it is crucial for this study that simulations are done using a leaf-like structure. Plants consist mainly of water, and although pure water is known as an excellent insulator, the minerals which are present in a plant do have conducting properties [19]. These minerals can be represented by salt. Therefore the choice was made to use salt water, of which the RF properties are known, during the simulations to represent the plant. However, while the RF properties of salt water are expected to lie close to those of plants, they are not exactly the same, because of the difficulty in determining the electrical properties of a plant. This could thus lead to results which could diverge from the measurements with real plants. This salt water, shaped like a plane, was added underneath the PCB. To connect the Antenna Booster directly to this salt water plane, initially copper layers were also placed on the edges of the PCB. These copper layers however, are difficult to realize in PCB manufacturing technology. Hence for the final design vias are used instead of these copper edges. The difference between the vias and the copper edges were found to be negligible. The PCB was made as small as possible, but big enough to accommodate the MN and the Antenna Booster. These choices were made to already get an indication whether the design including a salt water plane would be a plausible possibility. For future research removing the ground plane underneath the antenna area should be considered.

According to [17], there are two recommended possibilities on where to place the Antenna Booster on the PCB: one being at the corner and one at the center edge. In order to research both possibilities, the choice was made to place the PCB containing the Antenna Booster at either of those positions. The Antenna Booster was placed at the center edge of the PCB such that the PCB can contain the two MN's.

The two different set-ups and their E-fields are depicted in Fig. 3. It shows that the Antenna Booster in both cases seems to excite the PCB as well as the lossy salt water, which implies that the whole structure now contributes to the radiation. The E-field shown in Fig. 3a is similar to the E-field of a dipole antenna, while the E-field shown in Fig. 3b shows similarities to the E-field of a monopole antenna. The structure thus either operates as a dipole or as a monopole antenna depending on the location of the antenna booster.

B. PCB Dimensions

To understand the influence of the PCB dimensions, again the model proposed in [15] is used. Two PCBs with the same surface were used to test the effect different dimensions have on the performance of the structure. This was done to test whether for the final design only the surface of the PCB needed to be taken into account, or whether the dimensions also have a noticeable impact. Based on the the E-field distribution as shown in Fig. 3, it is expected that, next to the placing of the PCB, also the dimensions of the radiating structure are a key element in the design process. The results concerning total efficiency are listed in Table I. These simulations were done without a leaf, since this simple structure already provides the insight needed to design the final structure.

From Table I it can be concluded that an equal surface does not necessarily result in an equal total efficiency. However, it does emphasize that a difference in the width-length ratio has an impact on the total efficiency. This result was as expected and shows that when placing a PCB containing the Antenna Booster on different plant leaves, it will not result in the same efficiency. This proposes a design difficulty as it is not natural for leaves to be all the same size. A solution would be to design separate PCBs for different leaves. This however is a time consuming process. Another solution would be to place the PCB containing the Antenna Booster on leaves which dimensions are similar to one another, and accept the loss in efficiency for some leaves. Another point for discussion is that the direct impact of the PCB dimensions is uncertain. As was mentioned, the PCB dimensions do impact the radiation efficiency of the structure. There was however not a linear relation between PCB dimensions and radiation efficiency. An extension study could focus upon researching the effect of the PCB dimensions and how to use this to improve the final design. However, from these results can also be deducted that by simply changing the dimensions of the radiating structure, the total efficiency can be increased, which is positive for the hypothesis that adding a leaf to the structure of the PCB and the Antenna Booster can improve the efficiency.

C. Matching Network Design

The Antenna Booster is a passive component and can be tuned by using a MN [12], [17]. The MN was designed while taking the effect of the salt water plane into account. The implementation of the MN is done by using lumped elements in CST and by using the 0402-package [20]. The MN is implemented on the top layer of the PCB next to the location where the Antenna Booster can be placed and its schematic is displayed in Fig. 4. The structure is matched at a frequency of 2 GHz, which is in the operating range of the Antenna Booster [17].

TABLE I: Results concerning total efficiency difference of BT and GNSS between two PCBs with the same surface.

Width × Length	**Total efficiency BT**	**Total efficiency GNSS**
40 mm × 40 mm	74.7 %	12.8 %
80 mm × 20 mm	61.9 %	75.2 %

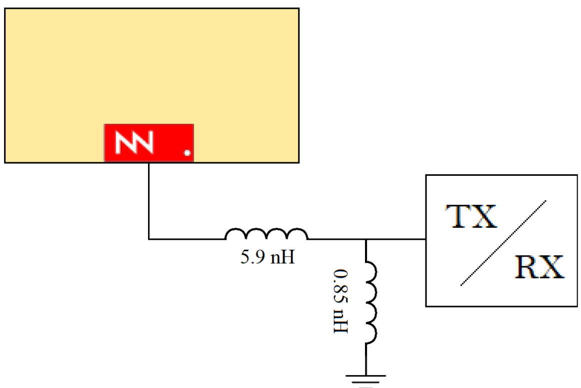
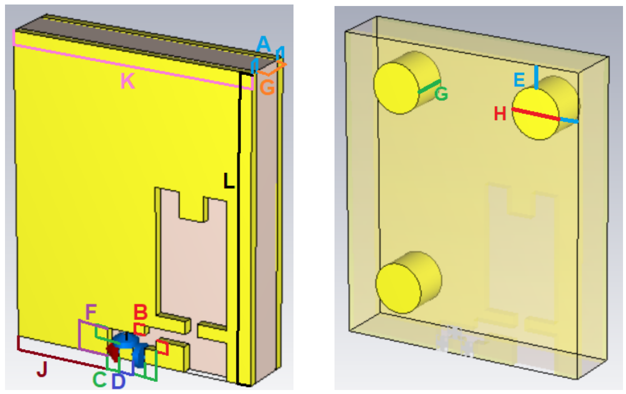


Fig. 4: The circuit of the MN which is implemented on the PCB in Fig. 5.



(a) (b)

Fig. 5: (a) The top layer, FR-4 substrate, and bottom layer of the PCB. (b) The vias connecting the top and bottom layer of the PCB.

TABLE II: Measurements of the PCB and salt water plane and the component values of the MN.

A	0.35 mm	**F**	1.1 mm	**J**	3.9 mm	**N**	18 mm
B	0.4 mm	**G**	1.55 mm	**K**	10 mm	**O**	23 mm
C	0.5 mm	**H**	2 mm	**L**	12 mm	**P**	49 mm
D	0.6 mm	**I**	3.2 mm	**M**	14 mm	**Q**	71.5 mm
E	1 mm						

D. Final Design

The final design which was used for the simulations is shown in Fig. 5. This final design is designed using [15], and by using the parameters of interest as described in Sections II-A, II-B, and II-C. The size of the final PCB is just large enough to contain the Antenna Booster and MN to minimize the size of the PCB and to maximize the contrast between the PCB and salt water plane dimensions. This ensures that the main radiating structure will be the salt water plane.

In Fig. 5a the top layer, FR-4 substrate with a relative permittivity ε_r of 4.3 and a loss tangent δ of 0.025 and part of the bottom layer are shown. The PCB also includes a bottom copper layer which ensures electrical connection between the antenna booster and the salt water plane. Fig. 5b shows the three vias connecting the top and bottom layer. The dimensions of this final PCB are listed in Table II. The Antenna Booster footprint dimensions are as mentioned in [17].

III. Simulation Results

This section includes simulations of structures consisting of the Antenna Booster mounted on the PCB, and a salt water plane in the form of an Aloe Vera leaf. The aim of these simulations is researching if adding a salt water plane can improve the radiation efficiency. Therefore in this section not only the question whether the Antenna Booster can excite a plant is answered, but also if this can give beneficial results and whether the design is robust.

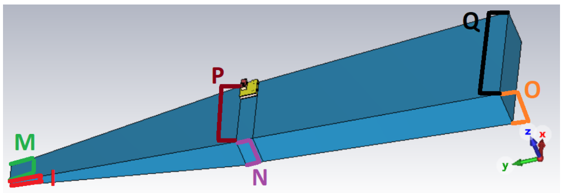


Fig. 6: The PCB design as shown in Fig. 5 including the DUO mXTEND and the salt water plane.

A. *Salt Water Simulations*

In Fig. 6, the PCB from Fig. 5 together with the Antenna Booster and the salt water plane is shown. The dimensions of the salt water plane are determined by taking the approximate dimensions of an Aloe Vera leaf. The measurements of the salt water plane as depicted in Fig. 6 are stated in Table II. The PCB is placed at the center edge of the salt water plane. This arrangement will be referred to as arrangement A from now on.

The reflection coefficients from the PCB with and without the salt water plane are shown at the top in Fig. 7. Comparing the reflection coefficients with and without the salt water plane, there is a clear shift in frequency between the two. This result is as expected, since the MN was designed while considering the effect of the salt water plane. The radiation efficiencies of the PCB with and without the salt water plane are shown at the bottom in Fig. 7. Here it is shown that for this design, the salt water plane can introduce an increase in radiation efficiency of approximately 9.6% at the frequency of 2.068 GHz. The realized gains of arrangement A with cut angles $\phi = 0°$, $\phi = 90°$, and $\theta = 90°$ are shown in Fig. 8. For these cut angles, the main lobes have peak realized gains of -6.2 dBi, -4.1 dBi, and -5.7 dBi, respectively. Whilst the realized gains in the planes $\phi = 90°$ and $\theta = 90°$ can be seen to be quite omni-directional, in the $\phi = 0°$ plane a radiation null can be found in the direction $\theta = 225°$.

Since these results are obtained using simulations, validation by means of efficiency measurements is the topic of future investigation. The changing impedance of the antenna may be solved using a reconfigurable matching network [16] to achieve an improved total efficiency for different leaves with different properties.

B. *Salt Water Simulations with Different PCB Locations*

Section II-A elaborates that placing the PCB on the corner of the salt water plane results in a different mode of operation compared to placing the PCB as done in arrangement A. Therefore, two more simulations were performed where the PCB containing the Antenna Booster was placed first at the top, and then at the bottom of the salt water plane. These arrangements will be referred to as arrangement B and arrangement C, respectively. The reflection coefficients and the radiation efficiencies of these simulations are shown at the top and bottom in Fig. 7, respectively. From the reflection coefficients in Fig. 7 it becomes clear that placing the PCB

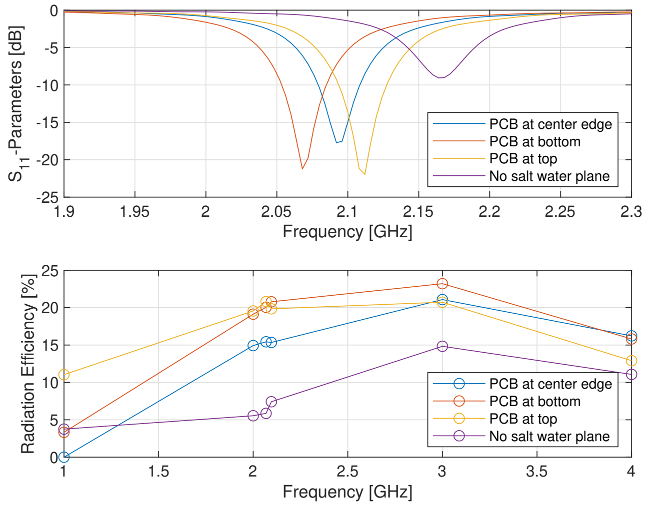


Fig. 7: S_{11}-parameters (top) and radiation efficiencies (bottom) of the design shown in Fig. 6, the design where the PCB is placed at the top of the salt water plane, the design where the PCB is place at the bottom of the salt water plane, and the design without the salt water plane.

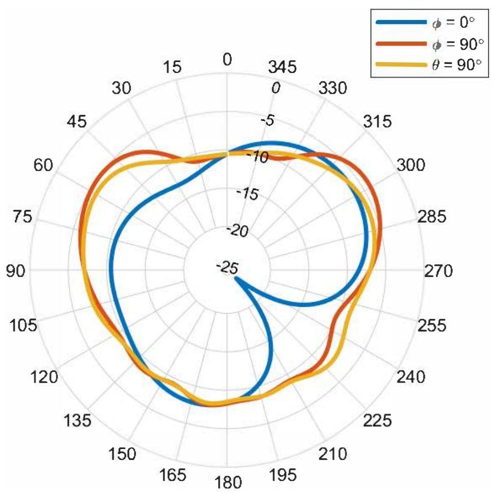


Fig. 8: Realized gains in dBi of arrangement A with cut angles $\phi = 0°$, $\phi = 90°$, and $\theta = 90°$ at the frequency of 2.096 GHz.

in either arrangement B or arrangement C introduces a shift in frequency compared to both arrangement A and when there is no salt water plane present. From the radiation efficiencies in Fig. 7 it can be concluded that these different placements can further increase the radiation efficiency to 20.8%, which is an increase of 15% compared to when no salt water plane is present.

C. *Salt Water Simulations with an Air Gap*

A leaf does not have an entirely flat surface, so there will likely be an air gap at some places between the leaf and the PCB when implementing the design in a physical test. For this reason, a simulation was done to study the sensitivity

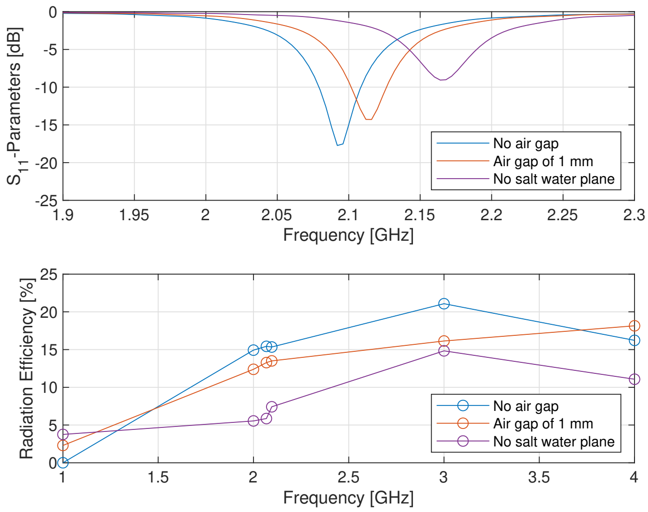


Fig. 9: S_{11}-parameters (top) and radiation efficiencies (bottom) of the design shown in Fig. 6, the design including an air gap of 1 mm, and the design without the salt water plane.

to an air gap between the salt water plane and the PCB. This simulation was done using arrangement A. The reflection coefficient and the radiation efficiency are compared to the reflection coefficients and radiation efficiencies of the case without an air gap and without a salt water plane and are displayed in the top and bottom of Fig. 9, respectively. From the top of Fig. 9 it can be concluded that introducing an air gap of 1 mm results in a shift in frequency of 30 MHz compared to the case without an air gap. This deviation is relatively small considering the working frequency range and does not affect drastically the matching performance. The bottom of Fig. 9 shows that around the frequency where the structure is matched the radiation efficiency decreases when an air gap is introduced. The air gap of 1 mm however still improves the radiation efficiency compared to when there is no salt water plane. Therefore it can be concluded from these results that an air gap does have an impact on the antenna performance, but can still ensure an increase in radiation efficiency compared to when the PCB is not attached to a leaf. Therefore it can be concluded that the structure is robust.

IV. Conclusion

This paper describes the research whether the Antenna Booster can excite a plant leaf. A PCB containing the Antenna Booster and a MN was designed in CST Studio Suite® and placed upon a leaf sized salt water plane representing a plant leaf.

Simulations show that an increase in radiation efficiency of 9.6% was achieved by adding the PCB containing the Antenna Booster to the center of a salt water plane. By placing the PCB at either the top or bottom of the salt water plane, an increase in radiation efficiency of 15% was achieved compared to when no salt water plane is present. Therefore it can be concluded that this implementation method holds promise for the future.

Introducing an air gap between the PCB and the salt water plane does have an impact on the final performance of the antenna. However, an air gap of 1 mm still improves the radiation efficiency compared to when no salt water plane is present. This indicates that an imperfection in the structure does not decrease the radiation efficiency drastically and that the structure thus is robust.

References

[1] Kevin Asthon, “That ’ Internet of Things ’ Thing,” *RFID Journal*, p. 4986, 2010. [Online]. Available: http://www.itrco.jp/libraries/RFIDjournal-That%20Internet%20of%20Things%20Thing.pdf

[2] J. Chin, V. Callaghan, and S. Ben Allouch, “The Internet-of-Things: Reflections on the past, present and future from a user-centered and smart environment perspective,” *Journal of Ambient Intelligence and Smart Environments*, vol. 11, no. 1, pp. 45–69, 2019.

[3] P. Asghari, A. M. Rahmani, and H. H. S. Javadi, “Internet of Things applications: A systematic review,” *Computer Networks*, vol. 148, pp. 241–261, 2019. [Online]. Available: https://doi.org/10.1016/j.comnet.2018.12.008

[4] "internet of things (IoT)". Accessed: 14-August-2021. [Online]. Available: https://internetofthingsagenda.techtarget.com/definition/Internet-of-Things-IoT

[5] J. Anguera, A. Andújar, and C. Puente, “Virtual Antenna™: Easy Design of IoT Devices with Embedded Antennas,” *Microwave Engineering Europe*, Sep-Oct 2019.

[6] L. Lizzi, F. Ferrero, P. Monin, C. Danchesi, and S. Boudaud, “Design of miniature antennas for IoT applications,” *2016 IEEE 6th International Conference on Communications and Electronics, IEEE ICCE 2016*, pp. 234–237, 2016.

[7] L. J. Chu, “Physical Limitations of Omni-directional antennas,” *Journal of Applied Physics*, vol. 19, no. 12, p. 1163, 1948.

[8] R. F. Harrington, “Effect of antenna size on gain, bandwidth, and efficiency,” *Journal of Research of the National Bureau of Standards, Section D: Radio Propagation*, vol. 64D, no. 1, p. 1, 1960.

[9] M. Stromlo, S. S. Observatories, and P. Bag, “Plantenna or a plant made to function as an antenna,” vol. 298, no. September, pp. 1134–1151, 1988.

[10] N. Rascio and F. Navari-Izzo, “Heavy metal hyperaccumulating plants: How and why do they do it? And what makes them so interesting?” *Plant Science*, vol. 180, no. 2, pp. 169–181, 2011. [Online]. Available: http://dx.doi.org/10.1016/j.plantsci.2010.08.016

[11] Ignion. (2021) "DUO mXTEND™". Accessed: 23-Apr-2021. [Online]. Available: https://ignion.io/product/duo-mxtend/

[12] J. Anguera, A. Andújar, G. Mestre, J. Rahola, and J. Juntunen, “Design of Multiband Antenna Systems for Wireless Devices Using Antenna Boosters,” *IEEE Microwave Magazine*, pp. 102–114, Dec. 2019.

[13] J. Anguera, A. Andújar, and C. Puente, “Compact antenna technology for wireless communications,” Patent WO 2020/120 589 A1.

[14] "CST Studio Suite Electromagnetic field simulation software". Accessed: 20-May-2021. [Online]. Available: https://www.3ds.com/products-services/simulia/products/cst-studio-suite/

[15] "Dassault Systemes: Embedding Virtual Antenna™ in IoT Devices with CST Studio Suite". Accessed: 24-Apr-2021. [Online]. Available: https://events.3ds.com/embedding-virtual-antenna-iot-devices-cst-studio-suite

[16] L. A. Bronckers, A. Roc’H, and A. B. Smolders, “A New Design Method for Frequency-Reconfigurable Antennas Using Multiple Tuning Components,” *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 12, pp. 7285–7295, 2019.

[17] *DUO mXTEND TM: TWO INDEPENDENT RADIOS IN THE SMALLEST ANTENNA FOOTPRINT*, Ignion Std. NN03-320 User Manual, 5 2021.

[18] J. Anguera, A. Andújar, C. Puente, and J. Mumbrú, “Antennaless wireless device,” Patent US. US 8,203,492 B2. 2012.

[19] "Conductivity (Electrical Conductance) and Water". Accessed: 25-Apr-2021. [Online]. Available: https://www.usgs.gov/special-topic/water-science-school/science/conductivity-electrical-conductance-and-water?qt-science_center_objects=0#qt-science_center_objects

[20] "Resistor Sizes and Packages: Resistor standards and codes: Resistor Guide". Accessed: 25-Apr-2021. [Online]. Available: https://eepower.com/resistor-guide/resistor-standards-and-codes/resistor-sizes-and-packages/#