Mm-wave wireless power transfer (WPT) system for wearable devices

Francesca Benassi, *Graduate Student Member, IEEE,* and Alessandra Costanzo, *Fellow, IEEE,*

***Abstract*—This project summarizes the design and optimization of a novel wireless power transfer system operating in the mm-wave range and making use of Bessel Beam Launchers as transmitting and receiving antennas. The system boasts high-focusing capabilities with relatively reduced dimensions that can be compatible with wearable applications. Two Bessel Beam antennas are described: a TM- and an Hybrid-TE polarized one. For each implementation a rectifier is designed and optimized by means of nonlinear simulations after rigorously evaluating the received power for different operating distances thanks to a custom numerical algorithm.**

***Index Terms*—WPT, Leaky Waves, Bessel beams, near-field focusing.**

I. Introduction

THE capability of transferring power wirelessly in the mm-wave frequency range has been raising a lot of interests in the scientific community, especially related to the miniaturization capability that those devices can achieve [1]. Most of the oeprating systems for WPT are designed to work in the Far-field, leaving the near-field for applications based on inductive or capacitive coupling working in the low-MHz or KHz frequency range. The presented project aims at describing the implementation steps and obtained results of a wireless power system, operating in the radiating near-field exploring Bessel Beam antennas. Bessel beams are nondiffractive solutions of the scalar wave equation, and some of their interesting capabilities such as non-diffractivity, high-focusing and self-healing [2] can make these type of antennas a novel candidate to be exploited within a WPT framework. In order to be applied in the biomedical environment, the main given constraints are the overall dimension of the receiving antenna but also the electrical decoupling of the antenna from the body surface. For this reason the described implementation makes used of truncated Bessel-Beam antennas, whose overall dimensions can be reduced up to an overall diameter of 30 mm without drastically affect the antenna radiating performance.

II. Project Description

The project has initially seen the investigation of two different types of Bessel Beam launchers, the first exciting a pure TM-leaky mode [3], whereas the second exhibits an Hybrid-TE one [4], to be applied in a wireless power transfer operative context, as schematically represented in Fig. 1.

Francesca Benassi is with the Department of Electrical, Electronic and Information Engineering Guglielmo Marconi (DEI), University of Bologna, 40136 Bologna, Italy (e-mail: francesca.benassi9@unibo.it)

Alessandra Costanzo is with the Department of Electrical, Electronic and Information Engineering Guglielmo Marconi (DEI), University of Bologna, 47522 Cesena, Italy (e-mail: alessandra.costanzo@unibo.it).

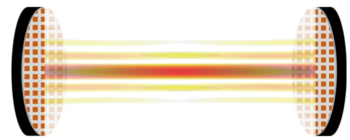

Fig. 1. Pictorial description of a WPT link made by two Bessel Beam launchers [3].

Both of them are based on FabryPerot cavity-like structures with approximately a $\lambda/2$-thickness and host a partially reflective surface (PRS) on the top layer. In order to generate a pure TE/TM-polarized BB, a vertical magnetic/electric dipole(VMD/VED) is required as excitation source. While TM-polarized Bessel Beams can be excited by means of a coaxial feeding, the generation os a pure TE-one is not trivial, as described in [4]. Given the dimensions constraints introduced by the operative context, the use of a truncated structure implies that the property of non-diffractivity is maintained up to a certain distance from the antenna aperture called nondiffractive range, that is related to the aperture radius ρ_{ap}, the order of radial resonance n and to $\bar{\rho}_n = j_{0n}/2\pi$ [4]:

$$\bar{z}_{\mathrm{ndr}} = \bar{\rho}_{\mathrm{ap}} \sqrt{(\bar{\rho}_{\mathrm{ap}}/\bar{\rho}_n)^2 - 1}, \tag{1}$$

with $(\bar{\cdot})$ referring to the normalization with respect to the vacuum wavelength λ_0.

The first designm presented in [3], is mainly centred on the rectenna design after establishing an accurate estimation of the link power budget by means of a custom made algorithm that exploits the Reciprocity and Equivalence theorems [5]. The TM-polarized Bessel Beam launcher, fed by a coaxial cable, resonates at 37.5 GHz and the corresponding design parameters and radiating features are listed in Tab.I.

TABLE I
Design parameters and radiating features of the BB launcher [3]

Design Parameter	Value	Radiating Feature	Value
ρ_{ap}	22.3mm	S_ρ	9 mm
h	3.175 mm	C_ρ	20%
Z_{s}	$-j25\,\Omega$	z_{ndr}	24 mm

To be able to accurately dimension the rectifier, the received power range must be quantified. The approach to perform this calculation is based on the full-wave simulation of a single Bessel-Beam antenna, the extraction of the Electric and Magnetic components of the full-waved simulated EM field and the evaluation of the received power at different TX-RX distances, by means of a rigorous numerical algorithm [5].

TABLE II
RECEIVED POWER AT 37.5 GHZ [3]

TX-RX distance (mm)	P_{r} (dBm)
20	5.1
30	0.9
40	-5.5

This way, the computational time required to standard wireless link full-wave simulation is halved, leading to the results listed in Tab.II, obtained for a 13 dBm transmitted power [3].

In order to design the rectifier accordingly, optimization are conducted within the calculated power range with the aim of maximizing the $\eta_{\mathrm{RF-to-dc}}$, obtaining a 30% rectification efficiency for a received power of 0 dBm. Subsequently the research has been focused on the design of a WPT link exploiting Hybrid-TE-polarized Bessel-Beam launchers. The launcher is then dimensioned to resonate at 30 GHz while the dimensions constraints are set to ρ_{ap}=15mm. Instead of using a PRS, simulating a fixed impedance, this type of Bessel Beam antenna accounts for an annular strip grating derived on a 0.254 mm-thin 3003 Rogers substrate as shown in the pictorial representation of Fig. 2.

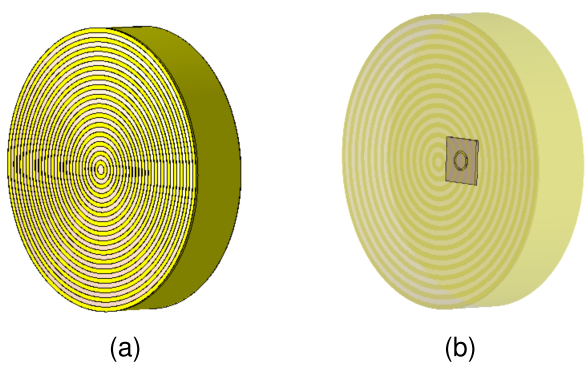

Fig. 2. Pictorial representation of the proposed Hybrid-Te Bessel Beam launcher showing (a) the annular strip grating surface and (b) the feeding loop.

To excite an Hybrid-TE, a loop antenna having $2\pi R \simeq \lambda$ derived on a Rogers substrate is used as a source [4]. This implemented structure is used to perform the power budget evaluation of the wireless link in which two Bessel-Beam antennas are used as transmitter and receiver. As previously described, the full-wave simulation is carried out only for a single antenna and the evaluation of the received power is rigorously conducted by means of the up-mentioned numerical procedure. The received power levels are computer for a transmitted power of 21 dBm, for three TX-RX operating distances of 20, 30 and 40 mm, and shown in Tab. III.

Having a planar loop as feeder allows to further compact the overall structure with respect to the TM-case. The optimized rectifier is design with a half-wave rectifier configuration and it is equipped with a matching network made of two short-circuit stubs to achieve a correct matching between the antenna input impedance $Z_A = 26.05 + j8.47\Omega$, and the rectifier input impedance that is approximately $Z_{RECT} \simeq 6.7 - j95\Omega$ for a 0 dBm input power. Optimized rectifier shows an $\eta_{\mathrm{RF-to-dc}}$ that is of about 30 % and 15% for a TX-RX distance of 30 and 40 mm respectively.

TABLE III
RECEIVED POWER AT 30 GHZ FOR THE HYBRID-TE BESSEL BEAM LAUNCHER [4]

TX-RX distance (mm)	P_{r} (dBm)
20	6.4
30	-0.6
40	-5.4

III. NEXT CAREER PLANS AND IMPRESSION ON IMS

Having the honour to be one of the recipients of the 2021 MTT-S Graduate Fellowship Award has given me a great opportunity to carry out my research activity as a PhD student. In the next future, I am planning to finish my PhD career and, if possible, to pursue an academic path in the field of wireless power transmission, to be able to transfer the acquired knowledge to whom will come next. The financial support provided by the MTT Society with this award has allowed me to further extend my research, broadening my knowledge in the field of mm-wave wireless power transfer. Unfortunately, I was not able to attend the 2021 IMS due to travelling restrictions related to the pandemic situation, but I think there will be other great opportunities to attend this important conference in the next future.

IV. AKNOWLEDGEMENT

I would like to express my most sincere gratitude to Prof. Giovanni Crupi and to the MTT-S Education Committee for this prestigious MTT-S Graduate Fellowship Award that has provided a significant contribution to my growth as a young researcher. I would also like to acknowledge my supervisors Prof. Alessandra Costanzo and Prof. Diego Masotti for their constant support and encouragement.

REFERENCES

[1] Q. Chen, Z. Liu, Y. Cui, H. Cai, and X. Chen, “A metallic waveguide-integrated 35-ghz rectenna with high conversion efficiency,” *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 8, pp. 821–824, 2020.

[2] W. Fuscaldo, A. Benedetti, D. Comite, P. Baccarelli, P. Burghignoli, and A. Galli, “Bessel-gauss beams through leaky waves: Focusing and diffractive properties,” *Phys. Rev. Applied*, vol. 13, p. 064040, Jun 2020.

[3] F. Benassi, W. Fuscaldo, D. Masotti, A. Galli, and A. Costanzo, “Wireless power transfer in the radiative near-field through resonant bessel-beam launchers at millimeter waves,” in *2021 IEEE Wireless Power Transfer Conference (WPTC)*, 2021, pp. 1–4.

[4] F. Benassi, W. Fuscaldo, E. Negri, G. Paolini, E. Augello, D. Masotti, P. Burghignoli, A. Galli, and A. Costanzo, “Comparison between Hybrid- and TM-polarized Bessel-beam launchers for wireless power transfer in the radiative near-field at millimeter waves,” in *Eur. Microw. Conf. (EuMC 2021)*, 2022, p. [Accepted paper].

[5] V. Rizzoli, D. Masotti, N. Arbizzani, and A. Costanzo, “Cad procedure for predicting the energy received by wireless scavenging systems in the near- and far-field regions,” in *2010 IEEE MTT-S International Microwave Symposium*, 2010, pp. 1768–1771.