Advanced Techniques for Wireless Power Transfer

Datasets on

Multi-Hop energy transfer

Work Package 1

Riga, 2023

1. MHN measurement setup overview in different WPT measurement scenarios

The evaluation of the MHN is divided into 3 sections: the first section is dedicated to the evaluation of the performance of the MHN with the log-periodic dipole array antennas (LPDA), where the PB and ESN were equipped with the log periodic antennas in line-of-sight (LoS) scenario, the MHN employs the Yagi-Uda antennas. This scenario examines the impact of the multipath signal propagation with reflections from the structure and its impact on the received power level depending on the distance compared to the scenario without the MHN. In this scenario, the LPDA antennas have wide beamwidth relative to the nearby objects and, therefore, will have an impact on the experimental results.

The second and third section experiments were set up to decrease the impact of the multipath signal propagation and reflections from the nearby objects and walls in a laboratory environment in LoS and NLoS scenarios by employing narrower beamwidth, high gain antennas – Yagi-Uda antennas with a gain of 9 dBi. In the second and third section experiments, all of the used antennas have the same type and gain. The experimental setup is set up in a different section in the room compared to the first section experiment, therefore cannot be directly compared depending on the distance between the PB and ESN due to multipath and reflections from nearby objects.

1.1 Overview of the MHN system evaluation of scenario in LoS conditions with LPDA antennas for PB and ESN

The experimental setup is shown in Fig. 1. The distance from the room wall in longitudinal length is 2 m, and from the side wall is 1.7 m. The distance between the PB and the MHN receiving antenna is 2 m, the distance between the MHN receiving and transmitting antenna is 0.3 m, and the distance between the MHN transmitting antenna and the ESN was varied from 1.5 m to 4.5 m. The PB and ESN both use the same antennas – LPDA antennas with a gain of 5 dBi. The MHN both antennas are Yagi-Uda antennas with a gain of 9 dBi.

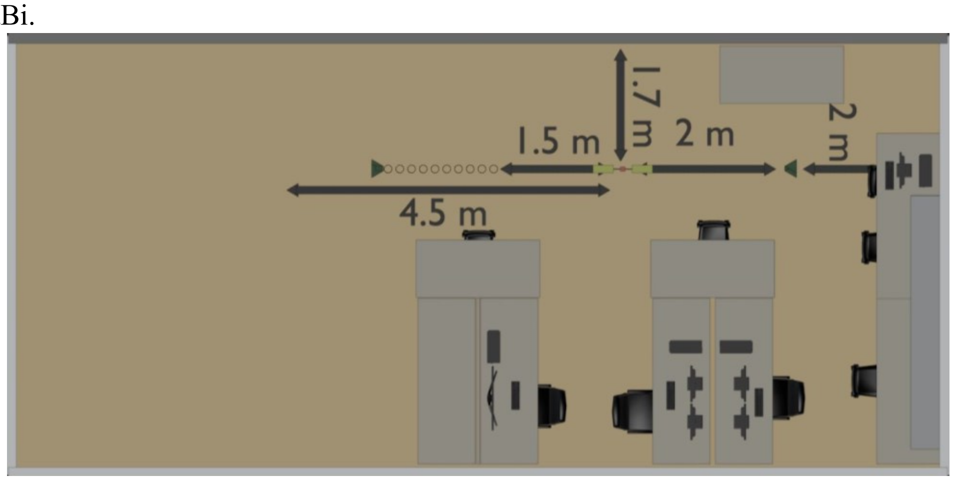

Fig 1. WPT setup for the LoS measurement scenario with Yagi-Uda antennas for the MHN and LPDA antennas for PB and ESN.

The evaluation of the MHN is performed in 4 different experimental setups, where the received power level is measured at the ESN antenna, and the rectified voltage level from the RF-DC rectifier at the ESN is measured with MHN and without it.

The setup of the measurements consists of the following equipment: signal generator R&S SMC100A with an additional external amplifier to perform as a transmitter – PB, the signal frequency is set to 865.5 MHz with the calibrated power level at the antenna measuring 27dBm power level. The PB and ESN employ LPDA antennas, and the MHN node- Yagi-Uda antennas. The measured power level at the ESN is measured with the oscilloscope Tektronix DPO72004C, where the received power level is measured in 50 Ω impedance mode to match the antenna impedance, later the measurement data is converted, and the input power level is calculated. The AD2 from Digilent is used to measure and save the rectified voltage levels for later processing. First, the measurements are performed with the MHN: the received power level and the rectified voltage level across the 5kΩ load resistor from the RF-DC converter at the ESN are measured, shown in Fig. 2. and Fig. 3. After that, the same experiment setup is performed without the MHN, shown in Fig. 4 and Fig. 5.

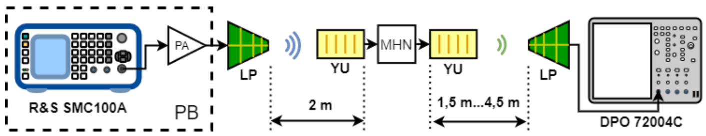

Fig 2. WPT measurement setup for evaluation of the MHN impact on the received power level at the ESN node depending on the distance between the PB and ESN.

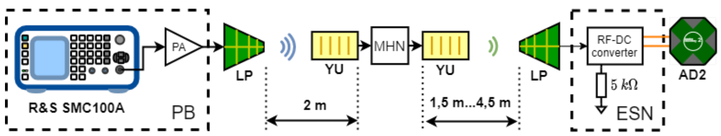

Fig 3. WPT measurement setup for evaluation of the MHN impact on the rectified voltage level at the ESN node depending on the distance between the PB and ESN.

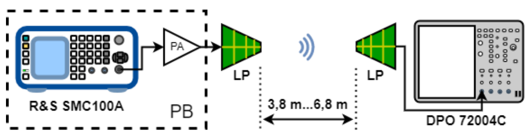

Fig 4. WPT measurement setup for evaluation on the received power level at the ESN node depending on the distance between the PB and ESN without MHN.

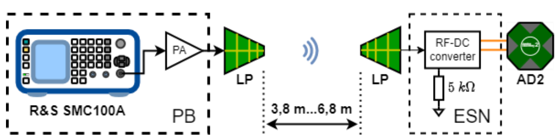

Fig 5. WPT measurement setup for evaluation of the rectified voltage level at the ESN node depending on the distance between the PB and ESN without MHN.

1.2 Overview of the MHN system evaluation of scenario in LoS and NLoS conditions Yagi-Uda antennas for PB and ESN

The second experiment is set up as follows: the PB, MHN, and ESN are set up in the LoS scenario, where all of the devices are aligned in one line. The antennas of the devices are located 1.7 m from the side wall, and the PB is located at around 1/3 of the room's length. The distance between the PB and MHN antenna's first dipole is set at 3.25 m. The distance between the MHN transmitting antenna's first dipole and the ESN first dipole is varied in range from 1.15 m to 3.4 m, shown in the Fig.6.

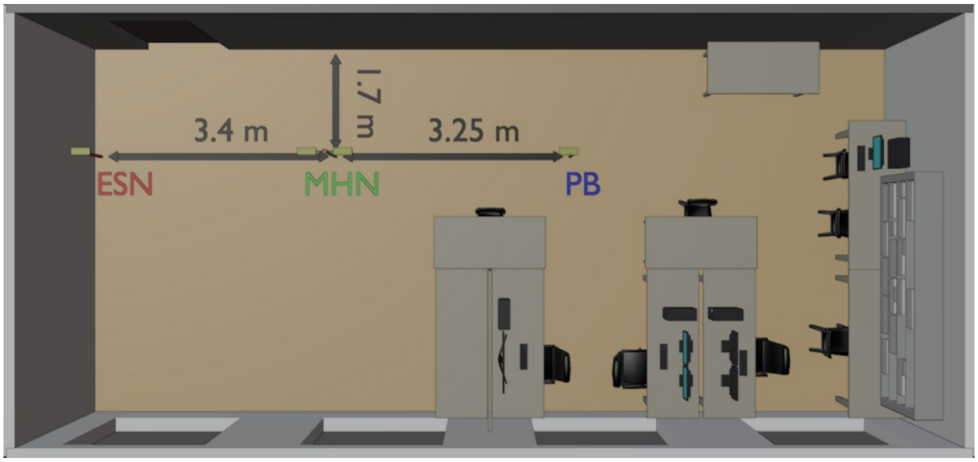

Fig 6. WPT setup for the LoS measurement scenario with Yagi-Uda antennas for the MHN , PB and ESN.

The third experiment is set to minimize the impact of the direct transmitted signal from the PB to the ESN and the resulting constructive or destructive interference in the received signal at the ESN. In this experiment, the PB transmitting antenna and the MHN receiving antenna are perpendicular to the MHN transmitting antenna and ESN antenna. The distance between the PB and MHN receiving antenna is set at the same distance as in the second experiment – at 3.25 m between both antenna's first dipoles and the distance between the MHN transmitting antenna and the ESN receiving antenna's first dipole was varied in the range from the 1.15 m to 3.4 m, shown in the Fig.7.

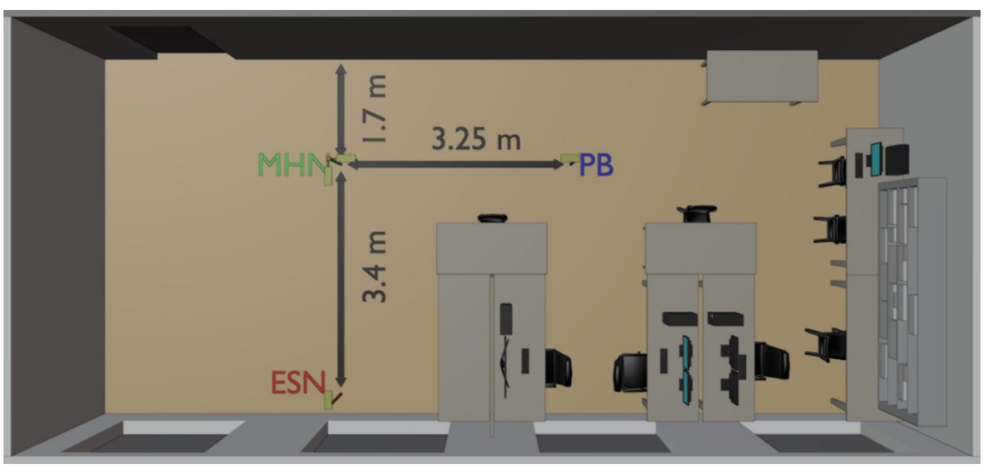

Fig 7. Preview of the LoS measurement scenario with Yagi-Uda antennas for the MHN, PB and ESN.

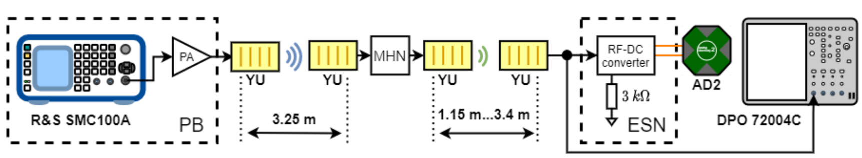

Fig 8. WPT measurement setup for evaluation of the MHN impact on the received power level and rectified voltage at the ESN node depending on the distance between the PB and ESN.

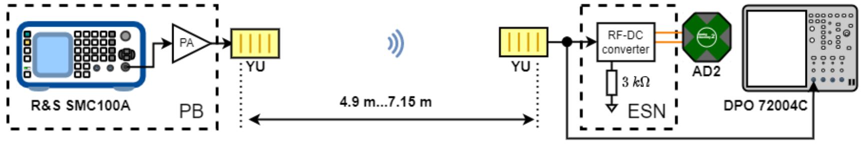

Fig 9. WPT measurement setup for evaluation of the received power level and rectified voltage level at the ESN node depending on the distance between the PB and ESN without MHN.

The setup of the WPT measurement with and without the MHN in NLoS conditions remains the same as in the LoS conditions, it differs only the actual placement of the MHN and ESN relative to PB. The measurement setup with the MHN for the received power and rectified voltage level with the RF-DC converter is shown in Fig.8, where for the received power measurements were performed by the oscilloscope Tektronix DPO72004C in the 50 Ω impedance mode directly from the antenna, the rectified voltage measurements were acquired by using AD2 from Digilent to measure and save the rectified voltage levels across the 3kΩ load resistor for later processing. The measurement setup without the MHN for the received power level and the rectified voltage level is shown in Fig.9. In these measurements the calibrated signal parameters at the PB antenna are as follows: 26dBm power level, with the frequency set to frequency of 865.5 MHz. The RF-DC rectifier design is the same, however differs with the iterations of it, as the rectifier in these measurements used low DCR RF inductors, that greatly improve the RF-DC power conversion efficiency, shown in Fig 10, the schematic with a variance in the matching network is given in the previous publications [1]. The peak power conversion efficiency of the RF-DC rectifier with the low DCR inductors is as such: 23% PCE with input power level of -20 dBm at 5 kΩ, 38% PCE with input power level of -15 dBm at 5 kΩ, 52% PCE with input power level of -10 dBm at 4.3 kΩ, 63% PCE with input power level of -5 dBm at 4.2 kΩ, 71% PCE with input power level of 0 dBm at 4.4 kΩ, 75% PCE with input power level of 5 dBm at 3.3 kΩ.

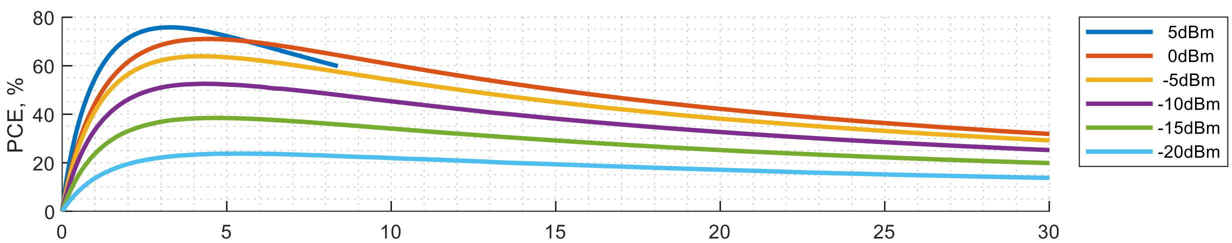

Fig 10. The power conversion efficiency WPT measurement setup for evaluation of the received power level and rectified voltage level at the ESN node depending on the distance between the PB and ESN without MHN.

2. Wireless power transfer performance evaluation of the different MHN scenarios

This section is dedicated to the analysis of the WPT measurement results with and without MHN with LPDA and Yagi-Uda antennas at the PB and ESN in LoS and NLoS conditions.

The first subsection is dedicated to the review of the MHN impact in LoS conditions when the PB and ESN employ LPDA antennas, but both of the MHN-employed antennas are Yagi-Uda antennas.

The second and third sections are dedicated to evaluating LoS and NLoS scenarios when all devices use high-gain Yagi-Uda antennas: PB, MHN, and ESN. The results between the first and second case cannot be directly compared, as the placement of the setup, and parameters differ. However, it will allow making an observation based on the measurement data with and without the MHN device, as well as the impact of the antenna types and environment impact on the results.

2.1 WPT evaluation of MHN performance in LoS scenario with LPDA antennas for PB and ESN

The received power level with and without the MHN in the WPT measurement LoS scenario with LPDA antennas for the PB and ESN is shown in Fig.11. The results are also compiled in Table 1. The results of both - the received power level and the rectified voltage level depending on the distance show a general trend, where the received power level decreases as the distance between PB and ESN increases. However, there are high fluctuations at the specific distances for both cases. The received power level for MHN at the ESN shows a mostly linear decrease of power depending on the distance from 1.6 dBm to -7.48 dBm in the distance range from 3.8 m to 5.3m, for the distance range from 5.45 m to 5.9 m, the received power level increases from -5.7 dBm to -4 dBm, then follows rapid decline up to -11.58 dBm at the distance of 6.2 m and then increases from then on up to -2.28 dBm at 6.8 m.

The same trend is observed for the measurement without the MHN, where the received power level with fluctuations decreases from -6.12 dBm to -13.24 dBm at the distance range from 3.8 m to 6.8 m, with the minimums found at the distances 4.85 m, 5.9m, 6.5m with the corresponding power levels of -15.75 dBm, -19.55 dBm, and -20.32 dBm.

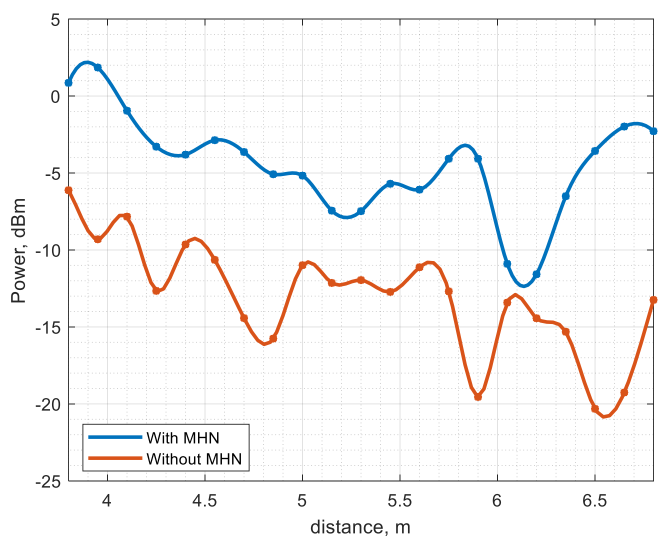

Fig 11. The received power level at the ESN in WPT LoS conditions with and without MHN depending on the distance between the PB and ESN with LPDA antennas.

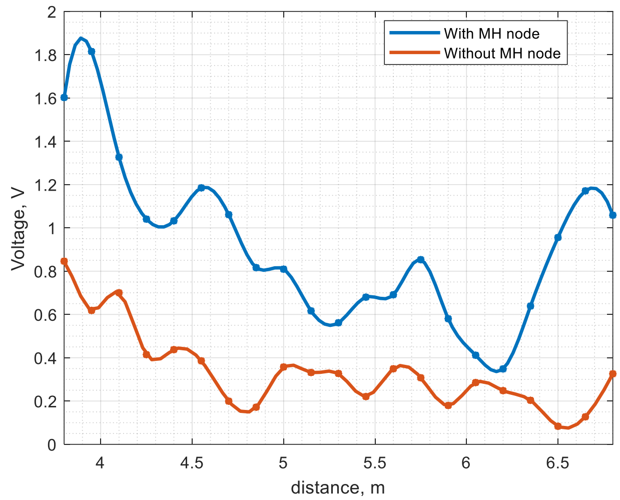

Fig 12. The received power level at the ESN in WPT LoS conditions with and without MHN depending on the distance between the PB and ESN with LPDA antennas.

Table 1. The received power level, rectified voltage level at the ESN with and without MHN with LPDA antennas for the PB and ESN.

dataset	**WPT LoS without MHN**		**WPT LoS with MHN**			
distance, m	Preceived, dBm	Vrectified, V	Preceived, dBm	Vrectified, V	Power gain (with MHN vs without MHN), dB	Voltage gain (with MHN vs without MHN), %
3.80	-6.12	0.85	0.86	1.60	6.98	189.34
3.95	-9.31	0.62	1.85	1.81	11.16	293.38
4.10	-7.83	0.70	-0.95	1.33	6.88	189.49
4.25	-12.66	0.41	-3.29	1.04	9.37	250.97
4.40	-9.64	0.44	-3.81	1.03	5.84	236.00
4.55	-10.64	0.39	-2.87	1.18	7.78	307.15
4.70	-14.43	0.20	-3.63	1.06	10.79	531.89
4.85	-15.75	0.17	-5.08	0.82	10.67	475.61
5.00	-10.99	0.36	-5.17	0.81	5.82	226.53
5.15	-12.14	0.33	-7.44	0.62	4.70	185.81
5.30	-11.96	0.33	-7.48	0.56	4.48	171.66
5.45	-12.72	0.22	-5.70	0.68	7.03	308.05
5.60	-11.12	0.35	-6.08	0.69	5.04	197.96
5.75	-12.69	0.31	-4.07	0.85	8.62	277.38
5.90	-19.55	0.18	-4.07	0.58	15.48	323.23
6.05	-13.42	0.29	-10.90	0.41	2.51	144.30
6.20	-14.44	0.25	-11.58	0.35	2.86	140.48
6.35	-15.31	0.20	-6.51	0.64	8.80	314.04
6.50	-20.32	0.08	-3.57	0.96	16.75	1143.50
6.65	-19.26	0.13	-1.98	1.17	17.28	920.65
6.80	-13.24	0.33	-2.28	1.06	10.96	324.93

The rectified voltage level at the ESN from the RF-DC rectifier across the 5 kΩ resistor with and without the MHN is shown in Fig. 12. In these measurements the rectified voltage level follows a similar trend to the received power levels at the ESN described in Fig. 11. Rectified voltage level at the ESN rectifier with MHN shows the mostly linear decrease of voltage level depending on the distance, in the distance range from 3.8 to 5.3m, the voltage decrease from 1.6 to 0.56 V, for the distance range from 5.45 m to 5.75 m, the rectified voltage level increases from 0.68 to 0.85 V, then follows rapid decline up to 0.35 V at the distance of 6.2 m and then increases from then on up to 1.06 at 6.8 m.

The same trend is followed for the measurement without the MHN, where the rectified voltage level with fluctuations decreases from 0.85 to 0.33 at the distance range from 3.8 m to 6.8 m, whereas the minimums measured at the distances 4.85 m, 5.9m, 6.5m with the corresponding rectified voltage levels of 0.17V, 0.18V and 0.08V.

The advantage of the MHN with this setup, where the PB and the ESN use LPDA antennas ranges from 2.86 dB to 17.28 dB gain in the received power level and increase of the rectified voltage level from the RF-DC rectifier from 140% up to 1143% with the load resistance of 5 kΩ.

2.2 WPT evaluation of MHN performance in LoS and NLoS scenario with Yagi-Uda antennas for PB and ESN

In following measurements, all of the devices use Yagi-Uda antennas with a high gain of 9 dBi; the beamwidth is much narrower compared to the LPDA antennas, and the impact from the multi-path propagation un reflection should be less than in the measurements with the LPDA antennas.

The received power level with and without the MHN in the WPT measurement LoS scenario with Yagi-Uda antennas for the PB and ESN is shown in Fig.13. The results are also compiled in Table 2. The results of both LoS scenarios with and without MHN show a similar trend to the received power level and the rectified voltage level depending on the distance, where the received power level decreases as the distance between PB and ESN increases. However, there are observable fluctuations at the specific distances for both cases. The received power level for MHN at the ESN shows a mostly linear decrease of power depending on the distance from 11.67 dBm to 1.67 dBm in the distance range from 4.9 m to 6.25 m, for the distance range from 6.4 m to 7 m, the received power level increases from 2.4 dBm to 3.43 dBm, then follows decline up to 2.1 dBm at the distance of 7.15 m.

The same trend is followed for the measurement without the MHN, where the received power level fluctuates around the value of 0 dBm to -0.84 dBm in the distance range from 4.9 to 5.65 m, the received power level decreases further with fluctuations from -3.16 dBm to -16.02 dBm at the distance range from 5.8 m to 6.85 m, whereas, after that, reverse trend is observed, with the received power level increasing up to -10.66 dBm at the 7.15 m distance.

The rectified voltage level at the ESN from the RF-DC rectifier across the 3 kΩ resistor with and without the MHN in LoS conditions is also shown in Fig.12. In these measurements, the rectified voltage level follows a similar trend to the received power levels at the ESN described in Fig. 11. Rectified voltage level with MHN at the ESN shows the mostly linear decrease of rectified voltage depending on the distance, at a distance from 4.9 m to 6.25 m, where the voltage decreases from 4.99 V to 1.74 V, at the distance range from 6.4 to 7m, the voltage increases and fluctuates around 2 V, with a decrease at the last measurement around 1.61 V. For the measurement without the MHN, the rectified voltage level stays around a similar value and fluctuates around 1.3 V at the distance range from 4.9 m to 5.5 m, in the distance range from 5.65 to 6.75 m it decreases up to 0.06 V and increases up to 0.29 V at the 7.15 m distance.

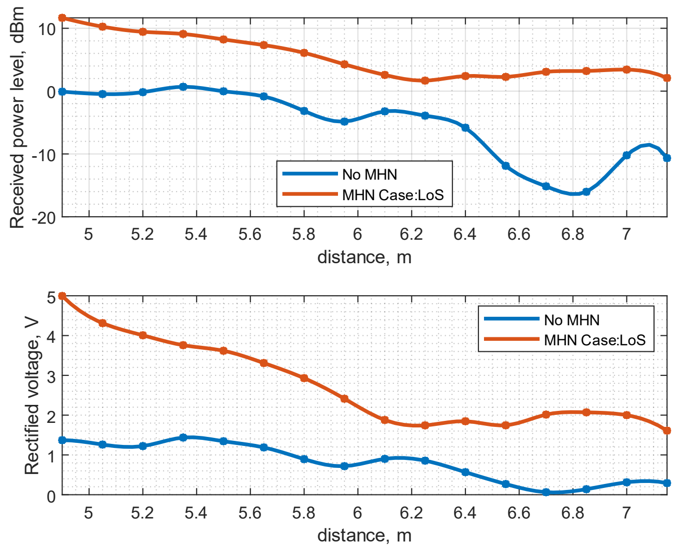

Fig 13. The received power level and rectified voltage level at the ESN in WPT LoS conditions with and without MHN depending on the distance between the PB and ESN with Yagi-Uda antennas.

The received power level with and without the MHN in the WPT measurement in NLoS conditions with Yagi-Uda antennas for the PB and ESN is shown in Fig.14, with the numerical data presented in Table 2. The results of NLoS scenarios with MHN, employing the Yagi-Uda antennas, show similar trend, where the received power level and the rectified voltage level decrease linearly up to some distance and then fluctuate around some value. The received power level for MHN at the ESN shows a mostly linear decrease of power depending on the distance. The decrease of power level is from 11.22 to 0.92 dBm in the distance range from 4.9 to 6.55 m, for the distance range from 6.7 m to 7 m, the received power level fluctuates around 1.21 dBm on average, then decreases up to -0.35 dBm at a distance of 7.15 m.

The rectified voltage level at the ESN from the RF-DC rectifier across the 3 kΩ resistor with and without the MHN is also shown in Fig. 14. In these measurements, the rectified voltage level follows a similar trend to the received power levels at the ESN. Rectified voltage level with MHN at the RF-DC rectifier from ESN antenna shows mostly linear decrease of rectified voltage depending on the distance, at a distance from 4.9 to 6.55 m the voltage decreases from 4.85 to 1.52 V, at the distance range from 6.4 to 7m, the voltage increases and fluctuates around 1.5 V, with a decrease at the last measurement around 1.32 V.

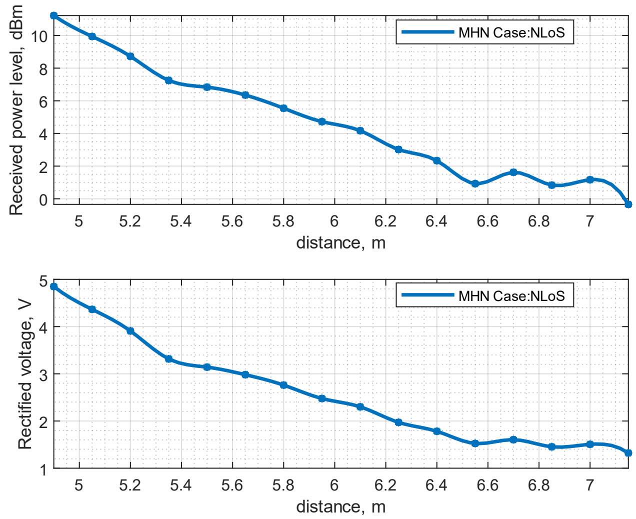

Fig 14. The received power level and rectified voltage level at the ESN in WPT NLoS conditions with and without MHN depending on the distance between the PB and ESN with Yagi-Uda antennas.

Table 2. The received power level, rectified voltage level at the ESN with and without MHN with Yagi-Uda antennas for the PB and ESN.

dataset	WPT LoS without MHN		WPT LoS with MHN				WPT NLoS with MHN	
distance, m	Preceived, dBm	Vrectified, V	Preceived, dBm	Vrectified, V	Power gain (with MHN vs without MHN), dB	Voltage gain (with MHN vs without MHN), %	Preceived, dBm	Vrectified, V
4.90	-0.08	1.37	11.67	4.99	11.75	364.33	11.22	4.85
5.05	-0.47	1.26	10.26	4.31	10.73	342.06	9.94	4.37
5.20	-0.17	1.22	9.44	4.01	9.61	327.81	8.72	3.91
5.35	0.69	1.44	9.09	3.76	8.40	261.53	7.25	3.32
5.50	-0.03	1.34	8.22	3.62	8.25	269.16	6.84	3.14
5.65	-0.84	1.19	7.33	3.31	8.17	278.45	6.35	2.98
5.80	-3.16	0.89	6.09	2.93	9.25	327.53	5.54	2.76
5.95	-4.85	0.72	4.27	2.41	9.11	336.04	4.72	2.48
6.10	-3.22	0.90	2.57	1.88	5.79	208.33	4.17	2.30
6.25	-3.91	0.86	1.67	1.74	5.58	203.65	3.02	1.97
6.40	-5.83	0.57	2.40	1.85	8.23	325.54	2.33	1.78
6.55	-11.89	0.27	2.27	1.75	14.16	649.77	0.92	1.52
6.70	-15.15	0.06	3.08	2.01	18.23	3189.50	1.62	1.60
6.85	-16.02	0.14	3.20	2.07	19.23	1489.70	0.84	1.45
7.00	-10.21	0.31	3.43	2.00	13.64	641.48	1.17	1.51
7.15	-10.66	0.29	2.10	1.61	12.75	551.52	-0.35	1.32

3. Conclusions

The efficient empirical approach to realizing the MHN-enabled WPT systems in the Sub-GHz frequency has been realized to increase the range of WSN devices and is described in this supplement and has been developed during the project implementation period. The approach relies on using the signal amplification method in conjunction with signal rectification for energy conversion and storage. A comparative experimental study has been performed to evaluate individual blocks of the MHN. The results of the MHN performance with different input power level conditions have been evaluated. The measurements have been performed with LPDA and Yagi-Uda antennas for the PB and ESN with MHN, where the results with LPDA show a much greater impact from multipath propagation and reflections from the indoor laboratory environment, the received power level at the ESN and the rectified voltage level at the ESN with MHN shows improvement in the measured power and rectified voltage levels.

The results with the MHN with Yagi-Uda antennas show much higher received power level and, therefore, also higher rectified voltage levels from the RF-DC rectifier at the ESN, the dependence on the distance is also with fewer fluctuations, as the antenna beamwidth is also narrower than with the LPDA antennas and there is much less impact from the multipath propagations.

References

[1] R. Kusnins, R. Babajans, D. Cirjulina, J. Eidaks, and A. Litvinenko, “Performance Estimation for RF Wireless Power Transfer under Real-Life Scenario,” in *2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON)*, Palermo, Italy: IEEE, Jun. 2022, pp. 1024–1029. doi: 10.1109/MELECON53508.2022.9843061.