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A Novel Yagi–Uda Antenna-Based Wireless Power Transmission (WPT) System Using Passive Reflectors †

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Abstract: This work examines how reflections from various reflective surfaces affect the reception of RF electromagnetic waves and how the latter impacts wireless power transmission. The frequency range used was 469.5 MHz to 773.5 MHz, and three reflective materials of almost 20% variation in the reflection coefficient were tested with a Yagi–Uda antenna at the receiving end. Additionally, the orientation of the antenna was changed in terms of elevation and azimuthal angles. The results were then assessed, and a conclusion was drawn.

Keywords: signal strength; energy harvesting; wireless power transmission; reflectory media; reflection coefficient

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1. Introduction

Radio frequency signals provide an endless source of energy due to their widespread presence in our lives. Whether they are television, cell phones, point to point, or Wi-Fi transmissions, they have surrounded us with various data and information transmission formats. While the use of this form of energy has been primarily for information transmission, it can also be used for power transmission and to provide operational energy to devices connected to an energy harvesting system. Both inductive and radiative mechanisms can be used for power transmission in the near- and far-field emission topologies [1].

The radiative mechanism is better suited for larger distances between the transmitting and receiving nodes. Harvesting, converting, and storing such energy is now possible. A typical energy harvesting system comprises four stages: exciting the antenna with incoming electromagnetic waves, rectifying the power at the output of the antenna, converting the power to desirable voltage and current levels (preferably DC), and storing the energy in a capacitor or battery for further use [2].

Harvesting ambient energy begins with a RF source, such as a television or radio transmitter, which is capable of transmitting continuous power in the form of data signals. These transmitters emit power evenly in all directions, with a gradual decrease in power levels proportional to the distance from the source. It should be noted that the power levels, when calculated numerically, lie in a range from picowatts to microwatts. Any energy harvesting device that needs to be powered by such power levels should be placed at a certain distance from the source in order to function properly.

Thus, the power requirement of the load is the key factor that would determine the distance from the source for the proper operation of the device. Thus, a radius from the source could be visualized within which the device to be used through energy harvesting could work properly by utilizing the harvested energy.

To boost the received power, a number of initiatives could be employed. One of the novel schemes could be a reflective medium that is capable of reflecting electromagnetic waves in a systematic manner such that the reflections and re-reflections from the surface could eventually end up in enhancing the signal strength at the receiving node. Using an intelligent reflecting surface (IRS) has recently emerged as a new technique that adapts with the propagation environment to enhance the spectrum and energy efficiency. In practice, an IRS consists of multiple individual sub-wavelength-reflecting elements that adjust the amplitude and phase of the incoming signal, a technique that comes under the umbrella of passive beamforming [3,4].

RF power can be converted into DC by the use of efficient rectenna-based power conversion systems. It has been shown that a voltage level of 1.8 V has been obtained over a 12 kΩ resistor for a 10 $\mu W/cm^2$ power density at a frequency of 1.8 GHz through a rectenna system that is capable of 61% efficiency [5]. The power levels have been reported to be measured at a distance of 10 m from the transmitter. Highly efficient rectenna systems have been reported to be fabricated that have been designed to collect more ambient RF power with an improvement in the power conversion efficiency (PCE) of about 61.4% and 31.8% at −5 and −15 dBm, respectively, for a 2.45 GHz frequency [6]. Novel techniques such as the use of the multiport pixel rectenna can result in enhanced harvested RF power for a given area as well as a reduction in the antenna matching requirements [7]. Rectenna-based systems as well as IRS-oriented solutions for highly efficient energy harvesting have resulted in a new era of efficient energy trapping systems. Different elements of an IRS have been reported to reflect independently the incident signal by controlling the amplitude or phase with the use of these massive low-cost passive reflecting elements integrated on a planar surface [8].

This paper is based on a novel model implemented through a test facility in which RF frequencies in the range 469.5 MHz to 773.5 MHz are transmitted for propagation in a closed environment first and then the effect of reflections from a reflective surface under various operating conditions are observed through the received signal strength. The receive antenna is the Yagi–Uda antenna.

2. Experimental Setup

The experimental setup consisted primarily of an antenna trainer with the provision of 13 different antenna configurations within the above-mentioned frequency range in MHz. However, the experimentation was performed on the Yagi–Uda antenna alone. The separation between the transmitter and receiver was set to be approximately 4 m firstly for the no-reflection condition; i.e., the transmission was primarily a line-of-sight transmission without any assistance to the receive signal strength due to reflections. After recording the received signal strength without any reflecting medium, various permutations and combinations were tried for different reflection surface geometries and to determine their impact on the received signal.

Reflecting Medium Geometries

The first set of observations were made without any reflection surface interaction with the transmission, i.e, it was a simple line-of-sight transmission at the specified distance of a 4 m separation between the transmitting and the receiving antenna. The next set of observations were made with the maximum number of possible reflecting surfaces, i.e, a closed tunnel like arrangement in which all the three dimensions were covered with the reflective surfaces. A number of readings were also taken by varying the reflective surfaces under the various conditions specified.

3. Hardware Details

3.1. The RF Generator

The RF generator used for this work had a power supply of 190–230 VAC at 50 Hz. The output power was 1.5 W with an output impedance of 75 Ω. The output of the generator used was kept constant at ±1 dB by an ALC (automatic level control) acting before the

75 Ω load resistor which could be considered the output impedance of the generator. This ALC circuit could be disconnected whenever desired through a switch.

3.2. The Field Strength Meter

The field strength meter consisted of a measurement antenna of variable length, a voltage detector and a LED bar indicator. The received signal strength was graphically shown through a LED field strength display comprising ten levels.

3.3. The Yagi–Uda Antenna

The Yagi–Uda antenna (Figure 1), originally developed by Shintaro Uda and Hidetsugu Yagi in 1926, is a directional antenna composed of two or more parallel resonant antenna elements in an array format, with a single driven element connected to a radio transmitter and/or receiver through a transmission line. The additional "parasitic elements" with no electrical connectivity are usually a reflector element that is slightly longer than the driven dipole, placed behind in the opposite direction of the transmission, and has one or many directors, which are slightly shorter than the driven dipole and placed in front of the driven element in the intended direction of transmission. These elements receive and reradiate the radio waves from the driven element in a different phase, determined by their exact lengths, which allows the waves from the multiple elements to interact to enhance radiation in a particular direction, increasing the antenna's gain in that direction.

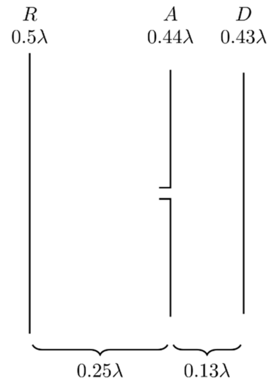

Figure 1. The basic Yagi–Uda antenna.

The Yagi–Uda antenna requires the wires or rods that make up the parallel elements to be equi-spaced along its length. For VHF or UHF antennas, the rigidity of the elements is usually suitable, but at lower frequencies, spacers are recommended to keep the wires apart. If the elements are not insulated, it is necessary to prevent them from shorting. In certain instances, a flat feeder can also be employed.

4. Observations

The setup as explained above comprised transmission and reception test benches that were almost 4 m apart. The test bench provided options to insert and remove reflectors throughout its length. The reflectors were fully capable of forming a duct almost equal to the width of the transmit/receive system (approximately 1.5–2 m meters wide). It was possible to introduce reflectors on the path of electromagnetic waves in four different formations. 'A' stood for all reflectors, i.e, all reflectors on the four sides throughout the length of the transmission/reception system almost 5–6 m apart. 'L' stood only for reflectors only on the left side of the antenna, and 'R' stood for reflectors on the right hand side of the antenna.

Various reflector positions along with antenna orientations used in this work were coded as below (Table 1):

Table 1. Antenna Position/Orientation Code & its Meaning.

Code	Meaning
All L	All reflectors present; antenna orientation: left
All M	All reflectors present; antenna orientation: LOS
All R	All reflectors present antenna orientation: light
Top L	Only top reflectors present; antenna orientation: left
Top M	Only top reflectors present; antenna orientation: LOS
Top R	Only top reflectors present; antenna orientation: right
Front L	Only front reflectors present; antenna orientation: left
Front M	Only front reflectors present; antenna orientation: LOS
Front R	Only front reflectors present; antenna orientation: right
Left L	Only left reflectors present; antenna orientation: left
Left M	Only left reflectors present; antenna orientation: LOS
Left R	Only left reflectors present; antenna orientation: right
Right L	Only right reflectors present; antenna orientation: left
Right M	Only right reflectors present; antenna orientation: LOS
Right R	Only right reflectors present; antenna orientation: right
Back L	Only back reflectors present; antenna orientation: left
Back M	Only back reflectors present; antenna orientation: LOS
Back R	Only back reflectors present; antenna orientation: right
No L	No reflectors present; antenna orientation: left
No M	No reflectors present; antenna orientation: LOS
No R	No reflectors present; antenna orientation: right

As is obvious in the graphs (Figure 2), the normalized power received when no reflectors were used was around 0.38 whereas it attained a maximum value of 2 with all the reflectors placed and with a right-side orientation of the folded dipole antenna. This gave us a gain enhancement of almost 81%, which is a substantial achievement.

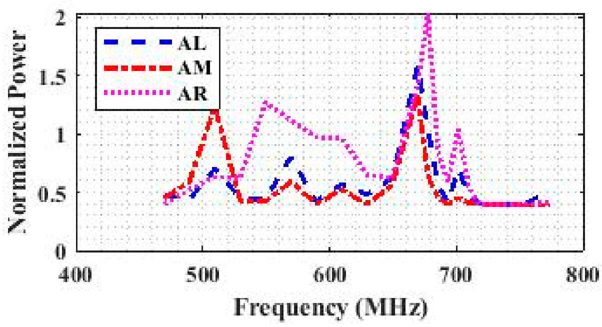

Figure 2. Yagi–Uda antenna observations.

5. Conclusions

'The table clearly shows that the enhancement in the receive signal strength for the Yagi-Uda antenna increased from a mere normalized power of 0.38 to a maximum normalized power of 2.08, when all the reflectors were present in the system and the antenna orientation was towards the right. The results were very positive with an overall enhancement in the received signal strength of about 81.3%.

This was a substantial enhancement in the received signal strength and can easily be utilized in the conversion of DC power enhancement with an all-passive power conditioning setup.

A substantial enhancement in the received signal strength was observed with the Yagi–Uda antenna when transmission and reception were carried out using passive reflectors. This can be a comparatively low-cost solution for effective wireless power transmission.

The above system could be used with a DC power conditioning unit (Figure 3) of the form shown below to convert this received signal strength enhancement into a substantial usable DC power system utilizing the wireless power transmission medium. It is expected that if a properly matched system can be formed, the DC power enhancement through a balanced rectenna system may end up to about 21% in the received signal strength. Further investigation and experimentation in this direction are solicited.

Figure 3. Basic AC to DC conversion/conditioning system.

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