

On the PAPR-Controlled Harvested-Power Crossover in Broadcast Wireless Power Transfer

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Abstract—Terrestrial broadcast infrastructure can supply wireless power to wide-area, low-power Internet-of-Things nodes, but the far-range coverage of such a link is limited by the nonlinear diode rectifier at the node. In broadcast wireless power transfer, raising the waveform peak-to-average power ratio (PAPR) is known to aid harvesting in the low received-power regime. Because a single broadcast waveform serves many nodes at widely different received-power levels at once, the received power over which this benefit holds is a practical question. Extending the view to a wider received-power range that includes rectifier compression, we show that the low-power benefit is one side of a redistribution: relative to a continuous-wave reference, raising the PAPR trades a near-range efficiency penalty for a far-range harvesting benefit rather than adding harvested power uniformly. We locate the crossover received power that separates the CW-favored near regime from the PAPR-favored far regime, and read it as a diagnostic boundary between the nodes that gain from high-PAPR signaling and those that lose. We attribute the far-range benefit to the rectifier's fourth-order nonlinearity and the near-range penalty to its compression beyond the small-signal regime, thereby extending a prior discrete-scheme observation of broadcast-WPT coverage.

Index Terms—Broadcast infrastructure, wireless power transfer, peak-to-average power ratio, rectifier nonlinearity, energy harvesting, coverage.

I. INTRODUCTION

Terrestrial broadcast infrastructure is a candidate energy source for wide-area, low-power Internet-of-Things (IoT) deployments. A broadcast tower covers a large service area from an elevated site. Its line-of-sight to ground-level nodes is generally stable. Radio-frequency (RF) energy can be supplied to many distributed nodes from a single transmitter, without dedicated power-beaming hardware. The approach suits remote or disaster-prone areas, in which battery replacement is costly and maintenance dominates the deployment lifetime [1]. Ambient and broadcast RF levels at such ranges are low, which places the design in the low-power energy-harvesting regime [2]. The system concept is shown in Fig. 1.

The performance limit of such a link is set at the node by the rectifier. Because the path loss over broadcast distances is large, the received power P_{rx} falls toward the Schottky diode turn-on threshold, where the RF-to-DC conversion efficiency

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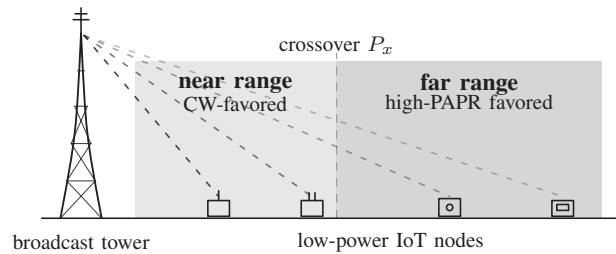


Fig. 1. Broadcast-based WPT concept: the near range is CW-favored and the far range high-PAPR-favored, split by a crossover received power P_x .

becomes low owing to the nonlinear diode characteristic [3]. Far-range coverage is therefore governed by the conversion efficiency at a weak input rather than by the transmitted power.

The transmitted waveform provides one means of acting on this efficiency. At a fixed average power, a waveform with a higher peak-to-average power ratio (PAPR) presents larger instantaneous peaks to the rectifier, and these peaks improve the harvested DC power in the low-power regime through the rectifier nonlinearity [3]. The influence of the waveform shape on the rectifier efficiency has been studied through behavioral rectifier models and multisine excitation [4], and formalized as a waveform design problem in [3]. These studies establish the low-power benefit of peaked waveforms at the level of the rectifier itself. High-PAPR signaling is therefore beneficial at low received power. A broadcast transmitter, however, supplies many nodes through a single waveform, and those nodes are distributed over a wide range of received powers. In a broadcast deployment the node population is fixed by the service area, and the received powers of the nearest and the farthest nodes differ by tens of decibels under the path loss of the link. A waveform decision made at the tower therefore acts on all of these operating points at once, and cannot be tuned to any single node. The received power over which the benefit holds is then a relevant design question rather than a fixed property of the waveform.

This question was examined in a prior broadcast WPT study [5], where a few discrete modulation schemes of differing PAPR were compared. High-PAPR signaling was found to extend coverage at long range while introducing a small

penalty at short range. The comparison was made at the level of individual schemes, so the received power at which the penalty turns into a benefit was not identified, and the origin of this reversal was not analyzed.

The present work extends this observation to a wider received-power range that includes rectifier compression. The low-power benefit reported earlier is retained and placed within this range. Relative to a continuous-wave (CW) reference, a higher PAPR reduces the harvested power at near range and increases it at far range, rather than increasing it uniformly; the harvesting advantage is thus redistributed along the received-power axis. To separate the channel from the rectifier, the harvested DC power is expressed as a function of received power P_{rx} rather than distance, and waveforms of differing PAPR are treated as discrete operating points. Three results are reported. First, the sign of the PAPR effect on harvested power reverses with received power, from a penalty at near range to a benefit at far range. Second, the crossover received power P_x at which this sign reverses is located, and the magnitude of both the penalty and the benefit is found to increase with PAPR. Third, within the cited rectifier model, the far-range benefit is attributed to the fourth-order nonlinearity and the near-range penalty to compression beyond the small-signal regime.

The analysis is carried out by simulation for a single-input single-output broadcast link with a Two-Ray ground-reflection channel and a nonlinear diode rectifier, both taken in cited form from [5] and [3] and stated as such in Section II. The link and rectifier configuration are held fixed so that PAPR remains the only variable. Section II defines the system and waveform model; Section III presents the crossover and its attributed origin; and Section IV concludes.

II. SYSTEM AND WAVEFORM MODEL

This section states the system, channel, and rectifier models used in the analysis. The Two-Ray channel and the nonlinear rectifier expansion are taken in cited form from [5] and [3]; they are restated for completeness and are not re-derived. The PAPR parameterization and the received-power formulation that follow are introduced here.

A. System and Channel Model

A single-input single-output (SISO) broadcast link is considered. One terrestrial tower acts as the energy source, and one low-power IoT node acts as the harvester. The tower is mounted at high altitude, so the propagation is dominated by a direct ray and a ground-reflected ray, and the channel is described by the Two-Ray ground-reflection model. For a transmitter–receiver separation d with $d \gg h_{\text{tx}}h_{\text{rx}}$, the received power P_{rx} is given, in the form stated in [5], by

$$P_{\text{rx}}(d) \approx P_{\text{tx}} G_{\text{tx}} G_{\text{rx}} \left(\frac{h_{\text{tx}} h_{\text{rx}}}{d^2} \right)^2, \quad (1)$$

where P_{tx} is the transmit power, G_{tx} and G_{rx} are the antenna gains, and h_{tx} and h_{rx} are the transmitter and receiver heights. For the present purpose, the relevant property of (1) is that P_{rx}

decreases monotonically with d . The mapping between d and P_{rx} is therefore one-to-one, which is used in Section II-D to place the analysis on a received-power axis.

B. Nonlinear Rectifier Model

The node harvests energy with a single Schottky-diode rectifier. The diode is nonlinear, so the harvested DC output depends not only on the average input power but also on the higher-order moments of the input waveform. This dependence is captured by the Taylor expansion of the diode characteristic. In the form stated in [3], the harvested DC output z_{DC} is

$$z_{\text{DC}} \approx k_0 + k_2 \mathbb{E}[v_{\text{in}}^2(t)] + k_4 \mathbb{E}[v_{\text{in}}^4(t)] + \dots, \quad (2)$$

where $v_{\text{in}}(t)$ is the rectifier input voltage and $k_0, k_2, k_4, \dots$ are diode-dependent coefficients. Odd-order moments vanish under the zero-mean assumption on $v_{\text{in}}(t)$.

All waveforms are compared under an equal-average-power constraint, $\mathbb{E}[v_{\text{in}}^2(t)] = \bar{P}$, where $\bar{P}$ is set by the operating point. Under this constraint, the second-order term $k_2 \bar{P}$ is identical for every waveform. The first waveform-dependent term in (2) is therefore the fourth-order term $k_4 \mathbb{E}[v_{\text{in}}^4(t)]$, so the fourth-order moment is the quantity that distinguishes one waveform from another in the harvested DC output. This property is the basis of the fourth-order attribution made later for the far-range behavior.

C. Waveform PAPR Parameterization

The waveform is not tied to a specific modulation format in this work. It is parameterized instead by a single scalar, its peak-to-average power ratio (PAPR),

$$\rho \triangleq \frac{\max_t |v_{\text{in}}(t)|^2}{\mathbb{E}[v_{\text{in}}^2(t)]} \geq 1, \quad (3)$$

where $\rho = 1$ corresponds to a constant-envelope continuous-wave (CW) reference and $\rho > 1$ to a peaked waveform. The waveforms considered here form a discrete set of such operating points, from the CW reference to higher-PAPR signals.

Under the equal-average-power constraint, a larger ρ concentrates the same average power into shorter and higher peaks, which raises the fourth-order moment. For a given waveform, this is written as

$$\mathbb{E}[v_{\text{in}}^4(t)] = \gamma(\rho) \bar{P}^2, \quad (4)$$

where $\gamma(\rho)$ is a non-decreasing shape factor whose minimum $\gamma(1)$ is attained by the CW reference. For the CW reference the instantaneous power is constant, so $\mathbb{E}[v_{\text{in}}^4(t)] = \bar{P}^2$ and $\gamma(1) = 1$; every peaked waveform has $\gamma(\rho) > 1$. Substituting (4) into the fourth-order term of (2) shows that the waveform-dependent part of the harvested DC output scales as $k_4 \gamma(\rho) \bar{P}^2$. The PAPR ρ is thus the handle through which the waveform acts on the harvested DC output.

D. Received-Power Formulation and Penalty Mechanism

The harvested DC output is governed by two separable factors. The channel in (1) sets the average input power $\bar{P}$ from the link geometry, and the rectifier in (2)–(4) maps $\bar{P}$ and the PAPR ρ to z_{DC} . To separate the geometry from the waveform behavior, the harvested DC output is expressed as a function of the received power P_{rx} rather than the distance d . The one-to-one relation in (1) makes this change of variable lossless and absorbs the geometry into a single scalar operating point, with $\bar{P} \propto P_{\text{rx}}$.

On this axis, the sign of the PAPR effect is not constant. At a low operating point the average input is weak, the rectifier stays in its small-signal regime, and the fourth-order term governs conduction; a higher ρ then raises z_{DC} , so a peaked waveform is favored. This far-range behavior is attributed to the fourth-order term of (2). At a high operating point the input is strong and the diode is driven beyond its small-signal regime. In this region the incremental conversion of instantaneous input power to DC output falls below its small-signal value, so the power carried in the waveform peaks converts sublinearly rather than in proportion; this behavior is referred to as compression in this paper. The peaks of a high-PAPR waveform are the first part of the waveform to reach this region as the operating point rises. The truncated expansion in (2) no longer describes this regime; its fourth-order term is positive and would still favor a peaked waveform. The near-range penalty therefore does not arise from (2) but from compression beyond the small-signal regime, which lies outside the truncated model and is captured phenomenologically in the simulation of Section III.

Because the PAPR effect is a benefit at low P_{rx} and a penalty at high P_{rx} , a crossover received power P_x exists at which a peaked waveform and the CW reference deliver the same harvested DC output, and across which the sign of the effect reverses, as indicated in Fig. 1. The existence and location of P_x are established by simulation in Section III.

III. SIMULATION RESULTS

This section reports the harvested-power behavior of peaked waveforms relative to the continuous-wave (CW) reference across received power, locates the crossover at which the effect of the peak-to-average power ratio (PAPR) reverses sign, and attributes the two-sided behavior to the rectifier model of Section II. The results are obtained by simulation and are presented on the received-power axis throughout.

A. Simulation Setup

The simulation setup is summarized in Table I. The simulation adopts the setup of [5]. A single broadcast tower and one low-power node are modeled over the Two-Ray ground-reflection channel of (1). The carrier frequency is 5.8 GHz and the average transmit power is 1 W; the transmit power is held fixed for every waveform, so the average received power, not the transmitted power, sets the operating point. The 5.8 GHz ISM band is adopted from [5], where it was selected to allow preliminary verification and future experimental validation

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Carrier frequency	5.8 GHz
Transmit power	1 W, fixed for all waveforms
Channel	Two-Ray ground reflection
Rectifier	Schottky diode (SMS-7630)
Received power P_{rx}	−50 to +15 dBm, 14 levels
Waveform PAPR	CW ($\rho=1$); 4.0, 5.5, 7.2 dB
Pulse shaping	RRC, roll-off 0.25

ahead of deployment in actual broadcast frequency bands. Each waveform is synthesized in MATLAB and injected into a single Schottky-diode rectifier (SMS-7630) in PSpice, where a transient analysis yields the harvested DC output; the diode follows the nonlinear model of (2) [3]. This MATLAB–PSpice co-simulation preserves the peak-to-average structure of each waveform through the nonlinear rectifier.

Following Section II-D, the harvested DC output is plotted against the received power P_{rx} rather than distance. The mapping in (1) is one to one, so no information is lost, and the rectifier behavior is isolated from the link geometry. The received power is evaluated at fourteen levels spanning −50 to +15 dBm, which covers both the small-signal regime and the compression regime of the rectifier. The waveforms form a discrete set of operating points: the constant-envelope CW reference ($\rho = 1$) and three peaked waveforms with PAPR of 4.0, 5.5, and 7.2 dB. The reported PAPR values are the envelope peak-to-average power ratio, referenced to CW and taken at the 99.9th percentile, of root-raised-cosine-shaped baseband waveforms with a roll-off factor of 0.25. Each waveform is identified by its PAPR value rather than by a modulation format, and all waveforms share the same average power.

B. The Harvesting-Gain Crossover

Fig. 2 shows the harvested DC power of the three peaked waveforms relative to the CW reference, expressed as a percentage gain, against the received power P_{rx} . For every waveform the relative gain is positive at low received power and negative at high received power, so a peaked waveform harvests more than CW at low P_{rx} and less at high P_{rx} . The sign of the PAPR effect therefore depends on the operating point, turning from a benefit into a penalty as the received power rises.

The relative gain is not monotonic in P_{rx} . It rises to a maximum near −25 dBm, declines into a shallow local reduction near −15 dBm, and then continues toward the negative high-power region. At this maximum the relative gain reaches +2.9%, +8.0%, and +13.3% for the three waveforms in order of increasing PAPR. The low-power benefit is therefore confined to a finite received-power range rather than growing without bound as the input weakens.

The shallow reduction near −15 dBm lies between the small-signal and compression regimes of the rectifier; it is recorded here as an observed feature of the simulated curves and is not analyzed further in this paper.

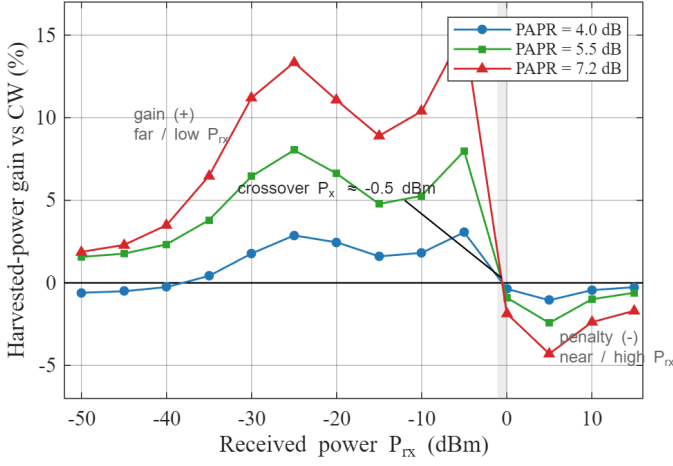


Fig. 2. Harvested DC power of three peaked waveforms (PAPR 4.0, 5.5, and 7.2 dB) relative to the CW reference, expressed as a percentage gain, versus received power P_{rx} . The waveforms are identified by PAPR. For each waveform the relative gain is positive at low P_{rx} and negative at high P_{rx} , and passes through zero within a narrow band near -0.5 dBm, where the sign of the PAPR effect reverses.

The relative gain passes through zero at the crossover P_x , which marks the received power that separates the CW-favored region from the high-PAPR-favored region. For the three waveforms the crossover falls near -0.5 dBm, within the resolution of the discrete received-power grid. On either side of this band the three curves keep their PAPR ordering: the 7.2 dB waveform shows the largest benefit below P_x and the largest penalty above it. At the $+5$ dBm operating point the penalty spans -1.1% to -4.3% across the three waveforms. The dependence of both magnitudes on the PAPR is examined next.

C. PAPR Dependence of the Gain and Penalty

Fig. 3 reports the relative gain at two operating points, one in the far range ($P_{rx} = -25$ dBm) and one in the near range ($P_{rx} = +5$ dBm), against the PAPR of the waveform. At the far-range point the benefit grows with PAPR, from $+2.9\%$ to $+13.3\%$ across the three waveforms; at the near-range point the penalty grows in magnitude, from -1.1% to -4.3% . Both grow as the PAPR increases. At a fixed operating point, therefore, the PAPR sets the size of the effect, while the received power sets its sign.

D. Rectifier Nonlinearity behind the Crossover Behavior

The two-sided behavior is attributed to two distinct features of the rectifier, following the model of Section II. Under the equal-average-power constraint, the first waveform-dependent term of (2) is the fourth-order term $k_4 \mathbb{E}[v_{in}^4(t)]$, which by (4) scales with the shape factor $\gamma(\rho)$. The far-range benefit is attributed to this fourth-order term [3]: at low received power the rectifier operates in its small-signal regime, where this term governs conduction, and a higher PAPR raises the harvested DC power.

The near-range penalty has a different origin. At high received power the rectifier is driven beyond its small-signal

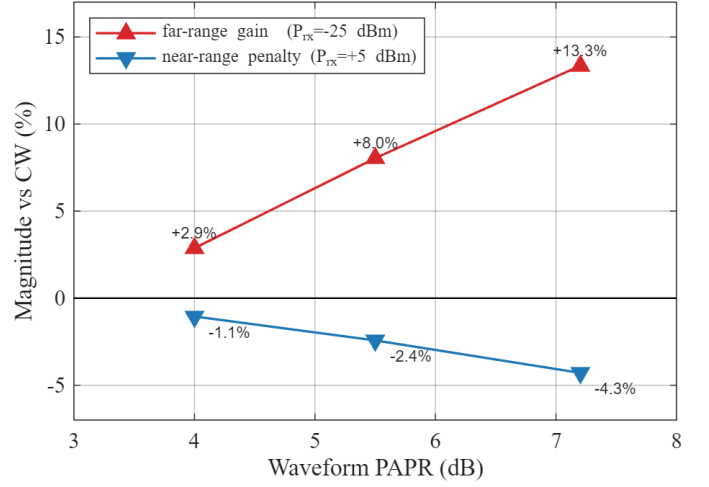


Fig. 3. Relative gain versus waveform PAPR (4.0, 5.5, 7.2 dB), at a far-range operating point ($P_{rx} = -25$ dBm) and a near-range operating point ($P_{rx} = +5$ dBm). The far-range benefit and the near-range penalty both increase in magnitude as the PAPR increases.

regime into compression, which the truncated expansion of (2) does not describe. The peaks of a high-PAPR waveform reach this compressed region, where extra peak power no longer converts in proportion, so a peaked waveform delivers less DC power than the constant-envelope reference. The penalty is therefore attributed to compression, not to the fourth-order term, which on its own would favor a peaked waveform.

The PAPR is used in Figs. 2 and 3 as an intuitive control variable, but the quantity to which the rectifier responds is the fourth-order moment rather than the PAPR itself. Under the equal-average-power constraint, the waveform enters the harvested DC output of (2) only through $\mathbb{E}[v_{in}^4(t)]$. The normalized fourth moment $\mathbb{E}[v_{in}^4(t)]/\mathbb{E}[v_{in}^2(t)]^2$, which is the shape factor $\gamma(\rho)$ of (4), measures the peakedness of the waveform and increases with PAPR, so the PAPR serves as a monotonic proxy for it. On this basis, the growth of the far-range benefit and the near-range penalty with PAPR in Fig. 3 is attributed to the increase of the fourth-order contribution $k_4 \mathbb{E}[v_{in}^4(t)]$ [3]. Because the driving quantity is the fourth moment and not the peak power, the magnitude increases monotonically with PAPR but is not proportional to it.

The crossover P_x is the received power at which these two mechanisms balance. The existence of the far-range benefit is therefore conditional: it requires the rectifier to operate in its small-signal regime over part of the covered received-power range. The matching network sets the operating point of the diode for a given received power, so the location of P_x depends on the rectifier configuration and not on the waveform alone. A rectifier matched to operate only in compression may instead show the near-range penalty alone, with no crossover inside the covered range. The reported location of P_x is accordingly specific to the fixed configuration of Table I; its dependence on the matching and the smoothing network is left to future work.

Because a single broadcast waveform reaches nodes across

a wide range of received powers, P_x marks the boundary between the nodes that benefit from high-PAPR signaling and those that do not, and so offers a diagnostic reading of a given deployment. For a given deployment, the received-power distribution of the nodes can be read against P_x to indicate which part of the node population stands on the gaining side of high-PAPR signaling and which on the losing side, before any change is made to the transmitted waveform.

IV. CONCLUSION

This paper examined high-PAPR signaling in broadcast wireless power transfer on a received-power (P_{rx}) axis and showed that raising the peak-to-average power ratio does not increase the harvested power uniformly. Relative to a continuous-wave reference, a higher PAPR reduces the harvested power at near range and increases it at far range, so the harvesting advantage is redistributed along the received-power axis rather than added across the whole range. Waveforms of differing PAPR were treated as discrete operating points and compared in simulation under a fixed link and rectifier configuration (Section III). The sign of the PAPR effect on harvested power reverses with received power, from a penalty at near range to a benefit at far range. The received power at which this sign reverses—the crossover P_x —was located, and the magnitude of both the benefit and the penalty was found to increase with PAPR. Within the cited rectifier model, the far-range benefit was attributed to the fourth-order nonlinearity and the near-range penalty to compression beyond the small-signal regime.

Relative to the earlier qualitative observation of a high-PAPR coverage advantage [5], the present contribution is to establish this two-sided behavior as a redistribution with a definite location and an attributed origin, rather than a one-sided gain. Because a single broadcast waveform serves nodes at many received powers at once, P_x also reads as a boundary between the nodes that gain from high-PAPR signaling and those that do not, a diagnostic for a given deployment.

A term-level separation of the fourth-order and compression contributions, together with the dependence of the crossover on the rectifier matching and the smoothing network, is left to future work. The range-dependent adaptation of the waveform is likewise deferred to subsequent study. Extending the analysis from the present line-of-sight setting to fading and shadowing channels, to multi-node deployments, and to hardware-prototype validation forms a longer-term direction. For wide-area broadcast WPT, the practical reading is that waveform peakedness repositions the received-power range over which the harvesting advantage is realized, rather than raising the harvested power uniformly.

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