Initial Report of Project: Waveform Optimisation for Information and Power Transfer

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I. Introduction

Wireless can be more than communications. Although cellular mobile communication has come to its fifth generation, wireless power delivery is still in the era of near-field inductive transfer with limited range. However, with the dramatic reduction in power requirements of smart devices, far-field wireless power transfer (WPT) has become possible for real-world applications [1] [2]. It has been predicted that the future of wireless may be to communicate and energise trillions of low-power devices [3]. In this project, a novel nonlinear energy harvester model based on the *i-v* characteristics of rectifier [4] is to be developed and compared with the conventional linear model where the transmitter, channel and receiver are assumed independent. We are to reproduce the result that for wireless power and information transfer (WIPT), the nonlinear model can provide a larger rate-energy region to the network, and a superposed waveform of modulated information and deterministic multisine power components can provide a two-fold benefit regarding information and power. Also, the time-switching (TS) receiver is favoured at low signal-to-noise (SNR) and for waveforms with a small number of sine tones, while power-splitting (PS) receiver is preferred on the opposite situations.

II. Theory and Methods

A. SWIPT Blocks

This project focus on the simultaneous wireless information and power transfer (SWIPT) architecture where the energy and information are transmitted and received at the same time. The energy receiver (ER) and the information receiver (IR) can be either co-located or separated.

Communication systems consist of three main blocks: transmitter, channel, and receiver. Therefore, the power delivered depends on not only the power sent, but also the power amplifier, the signal waveform, and the rectenna design. Figure 1 illustrates the scenario.

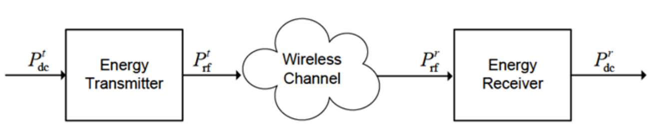

Fig. 1. Power in communication system [5]

Define overall efficiency $e = \frac{P^r_{dc}}{P^t_{dc}} = \frac{P^t_{rf}}{P^t_{dc}}\frac{P^r_{rf}}{P^t_{rf}}\frac{P^r_{dc}}{P^r_{dc}} = e_1 e_2 e_3$, the traditional analysis assumes e_1, e_2, e_3 are *linear* and to be optimised separately, which means e_1 and e_3 are independent of the power and shape of the input signal. However, the harvest nonlinear model emphasises the role of diodes in rectifiers in receivers. It indicates that although there are no randomness in efficiency e_1 that acts as a coefficient, not only e_2 but also e_3 is a *nonlinear* function of the input signal characteristics as waveform, modulation, beamforming, and input distribution. Hence, it is necessary to jointly optimise $e_2 e_3$ by a proper signal design to maximise the overall efficiency and enlarge the rate-energy region.

B. Diode Nonlinearity and Harvester Models

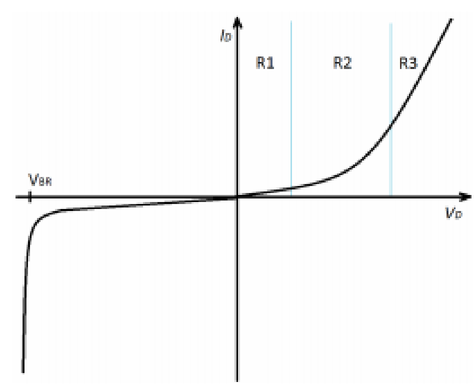

Fig. 2. Diode I-V characteristics [5]

Figure 2 plots the *i-v* characteristics of a diode. The diode DC current writes as

$$z_{dc} = \sum_{i \geq 2, even}^{n_0} k_i E\left[y_{rf}(t)^i\right] \tag{1}$$

where parameter k_i and output z_{dc} is independent of the quiescent operating point.

If approximating with the truncation order 2, the receiver input power $P^r_{rf} = E\left[y_{rf}(t)^2\right]$ is proportional to the output power $P^r_{dc} = z^2_{dc} R_L$. Therefore, the impact of power and shape of the received signal have been averaged out. It holds for very low received power P^r_{rf} where high order terms are negligible, as denoted by region 1 in Figure 2.

Nevertheless, things become complicated with the increase of received power P^r_{rf}, as truncating at higher order leads to nonlinear behaviour. In other words, receiver efficiency e_3 is related to the signal waveform. The harvester nonlinear model is suitable when the high order terms are not negligible that corresponds to region 2 of Figure 2. In the simulation, the advantages of diode nonlinear model regarding rate and energy will be demonstrated.

Region 3 corresponds to the diode breakdown region. It has been stated in [5] that it is not the purpose of the rectifier. It can be avoided by limiting the number of sine tones of the power component. Operating in this mode can reduce the efficiency e_3 significantly as denoted by the red curve in Figure 3. Therefore, this model is not considered in this project.

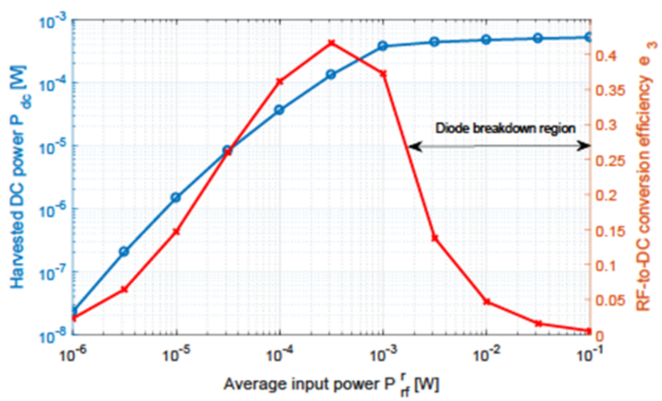

Fig. 3. Harvested DC power P^r_{dc} vs average input power P^r_{rf} and RF-to-DC conversion efficiency e_3 [5]

C. Multisine as Power Waveform

It is mentioned in [6] that using a multisine input signal can shift the transition region to a lower range from $[-20, 0]$ to $[-30, -10]$ dBm that brings diode nonlinear model and its advantages in a earlier stage. The characteristics of multisine are:

- High peak-to-average power ratio (PAPR)
- Concentrated power triggers the diode
- Pulse amplitude determined by number of tones N

D. Receiver Architectures

Figure 4 illustrates the diagrams of three possible receivers. In each case, the energy harvester (EH) and information decoder (ID) accept two individual streams for power and information respectively. The ideal receiver using the same signal for both ID and EH receivers is optimal but not realisable in current stage. TS receiver switch the signal to either ID or EH receiver at a time. It divides each transmission block into two mutually orthogonal power and data blocks, then optimise waveforms for individual blocks. Therefore, the rate-energy tradeoff depends on slot length and properties of transmit signals. PS receiver split a portion ρ of the signal to ID and allocate the rest $1-\rho$ to EH. In such cases, the transmitted signal can be optimised jointly and the rate-energy tradeoff is related to power-splitting ratio ρ and properties of transmit signals.

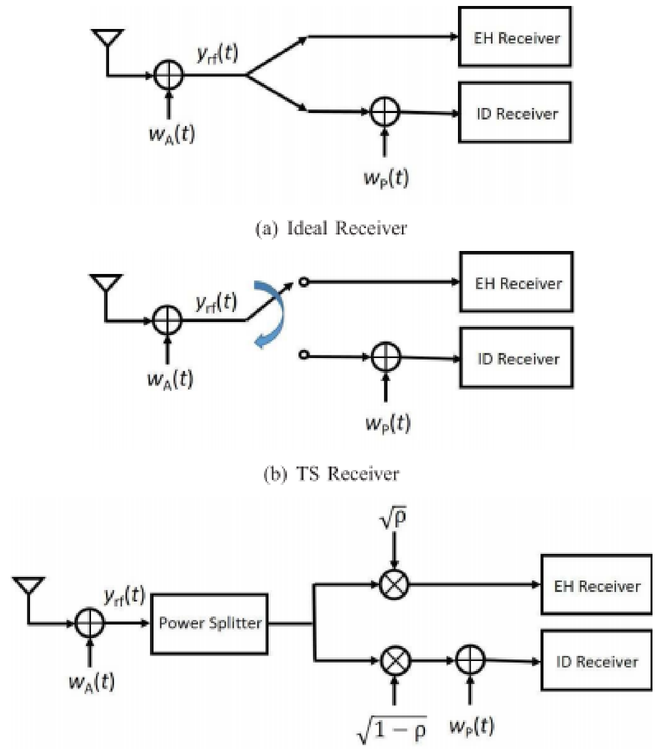

Fig. 4. Ideal, time switching (TS), and power splitting (PS) receivers [5]

III. Problem Formulation

The rate-energy (R-E) region is defined as

$$C_{R-E}(P) \triangleq \bigcup_{p(\mathbf{x}_0,\ldots,\mathbf{x}_{N-1}):Tr(\mathbf{Q})\leq P} \left\{ \begin{array}{c} (R,E): R \leq \sum_{n=0}^{N-1} I(\mathbf{x}_n, \mathbf{y}_n), \\ E \leq P^r_{dc}(\mathbf{x}_0, \ldots, \mathbf{x}_{N-1}) \end{array} \right\} \tag{2}$$

with the average transmit power constraint $Tr(\mathbf{Q}) \leq P$. It can be interpreted that

- Rate does not exceed mutual information
- Output current is no larger than diode DC current
- Power for energy and information purposes no more than budget

The optimisation problem turns into an energy maximisation problem

$$\begin{array}{c} \max_{\mathbf{S}_P,\mathbf{S}_I,\rho} z_{DC}(\mathbf{S}_P, \mathbf{S}_I, \Phi^\star_P, \Phi^\star_I, \rho) \\ s.t. \frac{1}{2}[\|\mathbf{S}_I\|^2_F + \|\mathbf{S}_P\|^2_F] \leq P, \\ I(\mathbf{S}_I, \Phi^\star_I, \rho) \geq \bar{R} \end{array} \tag{3}$$

which can be transformed to Geometric Program (GP) then solved by programs (*e.g. cvx*) using the algorithms proposed in [4] for single-input and multiple-input cases. The lower bound will also be investigated where the power waveform is circularly symmetric complex Gaussian (CSCG) distributed and the two-fold benefit disappears.

References

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