Low-Power Receiver Architecture for 5G and IoT-Oriented Wireless Information and Power Transfer Applications

Intikhab Hussain and Ke Wu
Poly-Grames Research Center, Polytechnique Montréal, Montréal, Québec, Canada
intikhab.hussain@polymtl.ca, ke.wu@polymtl.ca

***Abstract*— A low-power receiver architecture is introduced and studied for simultaneous wireless information and power transfer (WIPT) applications. The concept of WIPT is developed for energy-constrained wireless nodes without compromising the information receiver performance characteristics and the use of digital modulation techniques for 5G-oriented internet-of-things (IOT). With a diplexer-based six-port receiver, it is found that dedicated wireless power transfer is realizable along with simultaneous wireless information transfer. A multiport power recycling method is also deployed which exploits the unwanted harmonic signals generated by power detectors and signal interferers.**

***Keywords*—5G mobile communication, receiver, six-port, wireless power transfer, energy harvesting, power recycling, Internet of Things.**

I. Background and Introduction

With a megatrend towards the multi-level integration and addition of more standards, bands and functions, a flexible and efficient wireless transceiver architecture is indispensable for sustainable future applications. Recent cellular standards like 4G-LTE (Long Term Evolution) have been introduced for mobile devices, which are generally not optimized for low data rate and energy-constrained wireless nodes. However, the fifth generation (5G) mobile network aims to alleviate the limitations present in the previous standards and be a potential key enabler for future internet-of-things (IoT) [1]. Energy efficiency is perhaps the most important aspect of IoT as most of the IoT devices are battery-powered requiring a long time-period operation without human intervention.

The increasing demand of wireless connectivity as well as the over-crowded spectrum poses frequency selectivity-related design challenges on receivers. However, this issue opens up a new window to harvest energy coming from interferers. Radiofrequency energy harvesting network (RF-EHN) is an emerging concept to power next-generation wireless nodes through ambient energy or/and dedicated wireless power transfer nodes [2]. Energy management techniques such as lightweight protocols and scheduling optimization as well as energy harvesting play an important role in energy-constrained wireless networks [1].

Since RF signal carries information as well as energy, it is theoretically possible to extract RF energy from the same signal used for information decoding including demodulation. However, practical receiver hardware constraints the ability to harvest this energy as it is generally lost in the information decoding process [3]. There are different receiver architectures discussed in the literature with energy harvesting capability, namely separated antenna, time switching, power splitting and integrated rectifier [4, 5]. The separated antenna architecture provides the information decoder and energy harvester with observing in-band & out-of-band channels independently and concurrently. However, the separated antennas increase the size of wireless nodes. The time switcher and power splitter architectures share the same antenna to observe the same channels and their performance can be optimized by the ratio of time shared or power division between information receiver and energy harvester [6]. Nevertheless, different power sensitivities of information receiver and energy harvester poses significant challenges in the realization of such time switcher and power splitter architectures. In order to overcome the dynamic channel conditions, a tunable power splitting receiver topology was presented in [7] to maximize the energy harvesting with the minimum signal-to-noise ratio required for the information decoding at the expense of DC power consumption. Whereas, an integrated rectifier receiver (IRR) architecture exploits energy harvester rectification for down-conversion in time switching or power splitting mode, which is based on diode's self-mixing behaviour of signal tones. The self-mixing is prone to different distortions which limits the use of digital modulation techniques such as orthogonal frequency division multiplexing (OFDM) [8].

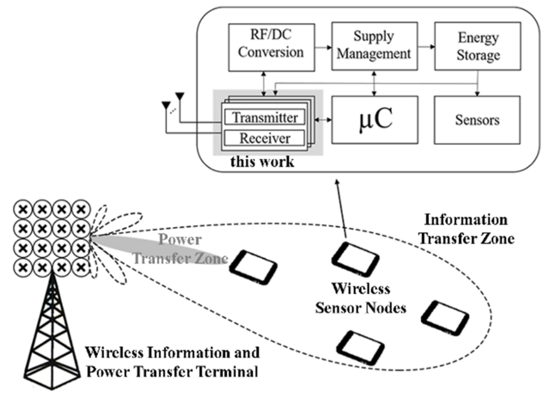

Fig. 1. Conceptual diagram of radiofrequency energy harvesting network (RF-EHN); WIPT terminal is capable of different frequency beams for information decoding and power transfer.

The objective of this work is to develop a concept for the development of wireless sensor transceivers that supports the wireless power transfer without compromising information receiver sensitivity and the use of well-established modulation schemes for information transfer. In the framework of this work, a low-power six-port receiver is studied that makes use of different frequency beams for information and dedicated power transfer and a conceptual diagram of RF-EHN is shown in Fig.

1. The low frequency signals have relatively lower path loss and the related frequency bands can be promising for dedicated wireless power transfer channels. This receiver architecture also benefits from the harvesting of out-of-band interferer signals. Furthermore, a multi-port power recycling method presented in [9] is also considered and incorporated in this work.

II. THEORETICAL ANALYSIS OF SIX-PORT RECEIVER

The six-port direct conversion architecture is very promising for low-power applications since its analog circuits require a very small power for operation [10]. The two input RF signals, namely received signal and reference signal, are superposed through a linear interference by a passive six-port junction under four different relative phases, which leads to four RF signals for down-conversion. The multi-port receiver uses zero-biased Schottky diode power detectors operated in the square-law region as opposed to conventional nonlinear mixers. The received modulated and reference signals can be represented by, respectively,

$$v_{RF}(t) = A_{RF}(I(t)\cos(w_{RF}t) - Q(t)\sin(w_{RF}t)) \qquad (1)$$

$$v_{LO}(t) = A_{LO}\cos(w_{LO}t) \qquad (2)$$

where $I(t)$ and $Q(t)$ are the in-phase and quadrature components of the modulated signal. In the square-law region of a power detector, the output voltage is proportional to the input power and it can be written as

$$v_{Ok} = \gamma_k P_k(t) = \gamma_k {v_k}^2(t);\ k = 1,2,\ldots,4 \qquad (3)$$

where

$$\begin{aligned} v_k(t) = {} & \alpha_k A_{LO}\cos(w_{LO}t + \theta_k) \\ & + \beta_k A_{RF}(I(t)\cos(w_{RF}t + \varphi_k) \\ & -Q(t)\sin(w_{RF}t + \varphi_k)) \end{aligned} \qquad (4)$$

where γ_k is a parameter dependent on the characteristics of power detectors, and α_k, β_k, θ_k and φ_k depend on the S-parameters of the six-port linear junction. Substituting (4) in (3) and assuming $w_{LO} = w_{RF} = w_c$, the following expression is obtained

$$v_{Ok} = \gamma_k {v_k}^2(t) \qquad (5)$$

$$= \gamma_k \begin{bmatrix} 0.5{\alpha_k}^2{A_{LO}}^2 + 0.5\,{\beta_k}^2{A_{RF}}^2(I(t)^2 + Q(t)^2) \\ +\alpha_k\,\beta_k\,A_{LO}A_{RF}(I(t)\cos(\theta_k - \varphi_k) + Q(t)\sin(\theta_k + \varphi_k)) \\ + 0.5\,{\beta_k}^2{A_{RF}}^2\cos(2w_ct + 2\varphi_k)(I(t)^2 - Q(t)^2) \\ +0.5{\alpha_k}^2{A_{LO}}^2 cos(2w_ct + 2\varphi_k) \\ +\alpha_k\,\beta_k\,A_{LO}A_{RF}I(t)cos(2w_ct + \varphi_k + \theta_k) \\ +I(t)Q(t)\,{\beta_k}^2{A_{RF}}^2 sin(2w_ct + 2\varphi_k) \\ -\alpha_k A_{LO}\,\beta_k A_{RF}Q(t)sin(2w_ct + \varphi_k + \theta_k) \end{bmatrix}$$

After a scalar detection, the output signals are low-pass filtered and passed to a subsequent digital-signal processing (DSP) section for information decoding. The first three terms stand for the self-mixing of oscillator signal, the self-mixing of modulated signal, and the mixing of modulated and local oscillator signals, respectively. The desired I/Q signal, which is hidden in the third term, is then obtained through a signal processing. The second harmonic of the RF signal, which is reflected back from the low-pass filter, can be recycled in energy-constrained wireless nodes.

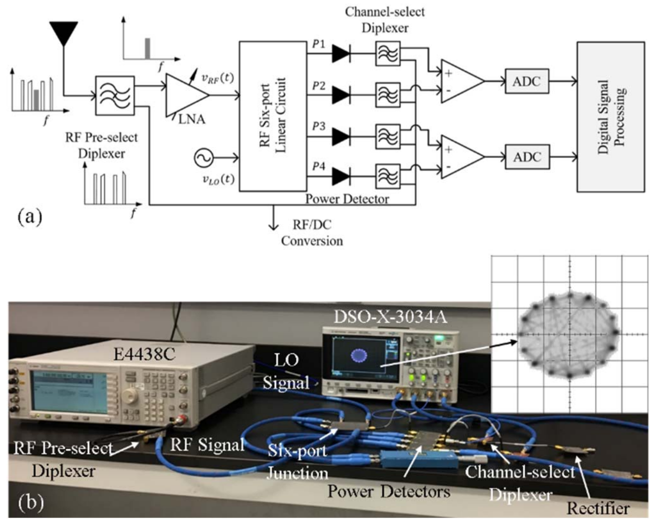

Fig. 2. Low-power diplexer-based six-port receiver for WIPT (a) its principle of operation (b) measurement test setup for information decoding and energy harvesting; Operating frequency = 3.6 GHz, Symbol rate = 100kSps, 16-PSK.

Table 1. Specifications of Six-port Receiver for WIPT

Component	Manufacturer and specifications
RF pre-select diplexer	Fabricated in PolyGrames Research Center, bandstop-bandpass topology, Insertion loss < 0.5 dB
Low-noise amplifier	Mini-Circuits ZX60-83LN-S+, 1.5 dB Noise Figure, 21.5 dB Gain
Six-port junction	Fabricated in PolyGrames Research Center, Wilkinson power divider and three 90-deg hybrid couplers
Power detector	Fabricated in PolyGrames Research Center using Skyworks SMS-7630 zero-bias Schottky diode
Channel-select diplexer	Mini-Circuits LDPW-162-242+, Insertion loss < 0.5 dB
Comparator and information decoder	Agilent DSO-X 3034A

III. DESIGN METHODOLOGY AND PERFORMANCE ANALYSIS

To overcome receiver design challenges related to the over-crowded spectrum, and support simultaneous dedicated wireless power transfer and out-of-band interferer energy harvesting, a diplexer-based six-port receiver architecture is studied, as shown in Fig. 2. The fixed diplexers are deployed to avoid the compromise of information receiver sensitivity and power consumption. The RF pre-select diplexer separates wireless power transfer frequency signals from the information frequency signals captured by the same antenna for rectification. The channel-select diplexers are used to recycle the power available in connection with the second harmonic of the received signal. A prototype is analysed in Keysight Advanced Design System (ADS) envelope simulator and measured using the building components listed in Table 1. Agilent E4438C vector signal generator is used to generate a pseudorandom bit train at a symbol rate of 100 ksps which corresponds to 400 Kbps for 16-PSK modulation scheme. The information bit stream is modulated at the carrier frequency of 3.6 GHz and the demodulated signal is directly visualized on Agilent DSO-X 3034A oscilloscope corresponding to complex vector $\Gamma = I + jQ$. The LO signal is phase-locked with the received signal to demodulate the phase information. This receiver works on the principle of separation of the frequency signals, receiver sensitivity, dynamic range and noise figure are thus mainly determined by power detectors and low-noise amplifier.

In order to demonstrate the power recycling concept, a zero-bias Schottky diode detector operating in the square-law region is designed and measured which is shown in Fig. 3. The lower bound of dynamic range is determined by tangential signal sensitivity (TSS), which is given by [11]

$$TSS_{dB} = NEP_{dB} + 4 + 5log_{10}B \qquad (6)$$

where noise equivalent power (NEP) is defined as the input power required to produce a unity output signal-to-noise ratio for a bandwidth of one hertz and B is the video bandwidth. The sensitivity of the power detector does not entirely depend on the diode characteristics in fact it is also related to the operating frequency, video bandwidth, video amplifier noise figure and diode bias current. The deviation from square-law characteristics occurs when the input RF power and, consequently the rectified current is high enough to affect the quiescent operating point of the diode [12]. The output power spectrum density of the detector, as shown in Fig. 4, infers that harmonics of the input signal retain useful energy that can be recycled to realize a power efficient wireless node. The measurement result shows that -23.04 dBm of power appearing at the output of SMS-7630 zero-bias power detectors in the second harmonic of the input signal. The overall performance characteristics of a power detector is determined by diode impedance, diode capacitance, DC bias current, video bandwidth, signal level, load impedance and RF signal frequency.

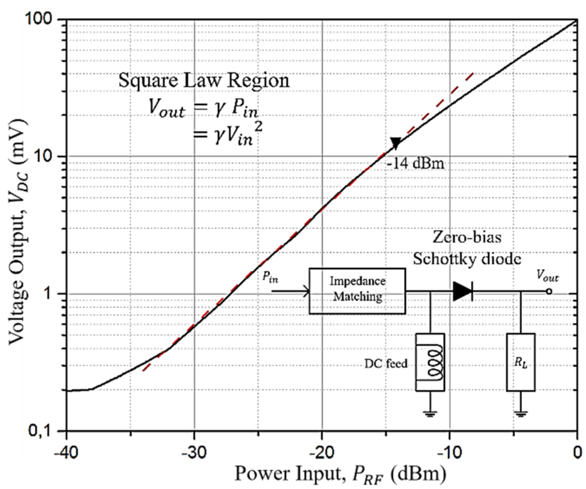

Fig. 3. Measured characteristics of SMS-7630 diode power detector for 50 Ohm load impedance; γ is the diode voltage sensitivity which depends on the input signal level, load impedance and RF signal frequency.

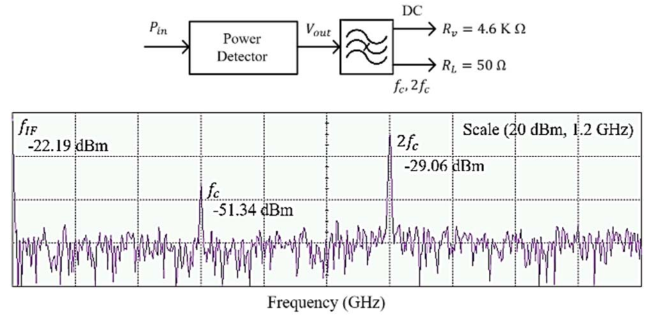

Fig. 4. Measured power spectral density (PSD) at the ouput of channel-select diplexer with P_{in} = -15 dBm at f_c = 3.6 GHz.

IV. Conclusion

This work presents a six-port receiver architecture which is based on the separation of frequency signals to support simultaneously wireless information decoding and power transfer. The measurement results have demonstrated that the proposed diplexer-based multiport architecture is realizable without conceding the receiver sensitivity, dynamic range and noise figure. It can also support digital modulation technique required for 5G-related internet-of-things (IoT) applications.

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