Wireless Information and Power Transfer: From Scientific Hypothesis to Engineering Practice

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Abstract

Recently, there has been substantial research interest in the subject of Simultaneous Wireless Information and Power Transfer (SWIPT) owing to its cross-disciplinary appeal and its wide-ranging application potential, which motivates this overview. More explicitly, we provide a brief survey of the state-of-the-art and introduce several practical transceiver architectures that may facilitate its implementation. Moreover, the most important link-level as well as system-level design aspects are elaborated on, along with a variety of potential solutions and research ideas. We envision that the dual interpretation of Radio Frequency (RF) signals creates new opportunities as well as challenges requiring substantial research, innovation and engineering efforts.

I. INTRODUCTION

1) Scientifically-Oriented Background: In thermal and statistical physics, the earliest and most famous remarkable experiment regarding information and energy was conceived by Maxwell in 1867, which is referred to as ”Maxwell’s Demon” [1], where the second law of thermo-dynamics was hypothetically violated by the bold hypothesis of information to energy conversion. This stimulated further intriguing research in the mid-20th century as to whether information processing itself dissipates energy, which subsequently led to ”Landauer’s principle” [2] suggesting that thermo-dynamically reversible manipulations of information in computing, measurement and communications do not necessarily dissipate energy, since no energy is required to perform mathematical calculations. Despite the fact that information to energy conversion is elusive, it was suggested from a fundamental perspective that the separate treatment of information and energy may have to be challenged in the practical design of engineering systems.

Naturally, information is carried by attaching itself to a physical medium, such as waves or particles. In molecular- and nano-communications, information is delivered by conveying encoded particles from the source to destination. Similarly, in optical communications, information is delivered by photons having information-dependent intensities, which may be detected by a photon-counting process. Given the nature of the process, the system is capable of providing a heating/illumination/propulsion function. Both of the above examples suggest that the underlying matter that carries information can be effectively reused for diverse applications. The explicit concept of transporting both information and energy simultaneously was raised by the authors of [3], which was recently further extended to the wireless regime [4], [5] since the underlying Electro-Magnetic (EM) wave can carry both information and energy. Thus, it is desirable that a mobile device is free from being tethered in any way.

2) Engineering-Oriented Background: Before delving into the topic of Simultaneous Wireless Information and Power Transfer (SWIPT) [4], [5], a brief introduction of Wireless Power Transfer (WPT) is warranted [6]. Generally speaking, WPT can be carried out in two basic ways, namely based on either *near-field* EM *induction* in the form of inductive coupling and resonant coupling relying on coils or with the aid of *far-field* EM *radiation* using microwave frequencies by relying on so-called rectennas. When compared to near-field EM induction that only tolerates a small misalignment between the transmitter

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and receiver, far-field Microwave Power Transfer (MPT) supports a wider coverage and thus it may be considered to be more suitable for employment in SWIPT systems.

The earliest experiments on MPT were conducted by Tesla with the ultimate goal of creating a worldwide wireless power distribution system. In the mid-20th century, MPT was conceived for high-power applications in the Mega/Kilo-Watt-range. The need for power increased substantially owing to the development of electronic devices in the late 20th century. In particular, research has been focused on the design of compact and efficient rectennas conceived for applications in the milli/micro-Watt-range, where the start-up company Powercast [1] has reported that micro-Watt-scale power was transmitted over a distance of a few meters at the transmission power of 23dBm at a frequency around 900 MHz.

As widely known across the wireless community, another innovative and revolutionary exploitation of EM wave propagation over the last century was Wireless Information Transfer (WIT), as inspired by the late-19th century radio-experiments conducted by Marconi, which eventually led to the mid-20th century tactical military use of radar in the Second World War and to the pervasive commercial revolution of the mobile industry. It is thus the maturing WPT and WIT fields that make the SWIPT an interesting emerging research topic.

3) Application-Oriented Background: Compared to the pervasive WIT, WPT is less well exploited at the time of writing, which is mainly due to the high attenuation of RF signals over distance. Thanks to the recent advances both in antenna technologies and in power electronics, a significantly increased power can now be transferred to wireless devices, which are themselves becoming increasingly more energy efficient. Thus, SWIPT becomes especially compelling in scenarios, where charging the battery is either of high risk or of high cost, as in medical implants, in-building sensors etc. To elaborate a little further, conventional energy harvesting relies on ambient energy sources (wind, vibrations and heat etc) and at the current state-of-the-art they are only capable of supporting low-rate communications. By contrast, the unique characteristic of a SWIPT system is that it is capable of operating in an environment having insufficient ambient energy sources, whilst delivering a controllable amount of wireless information and energy concurrently, hence supporting low-cost, sustainable operations.

Owing to the fact that the EM radiation is restricted by both health and safety regulations, it remains an open challenge at the current state-of-the-art to power a mobile phone, typically requiring around a few hundred milli-Watt power. Nonetheless, this technology is becoming more appealing for employment in low-power sensors. Consequently, it becomes promising for the family of near-future wireless systems with the goal of connecting billions of low-power devices globally. In this scenario, known as the 'Internet of Things' (IoT), SWIPT is expected to become a pervasive enabler, which is 'immortal' from an energy replenishment perspective. To be more specific, low-power sensor networks, wireless body area networks and long-distance Radio Frequency IDentification (RFID) networks would directly benefit from SWIPT techniques.

4) Organisation: Based on the above background, *we provide an overview of the emerging topic of SWIPT, commencing from a crisp literature review to elaborating on practical architectures as well as on their important design aspects and their potential solutions.* Our overview paper is thus organised as follows. We commence by surveying the existing literature of SWIPT in Section II-A, with an emphasis on its theoretical aspects. We then summarize the existing practical architectures facilitating SWIPT in Section II-B, where three potential architectures are introduced. This is followed by our elaborations on the key link-level components in Section III-A, ranging from multi-antenna aided techniques to both coding and modulation. These link-level components are the fundamental building blocks of system-level studies, as discussed in Section III-B, where we explicitly reveal the associated pros and cons of interference. Finally, we conclude our discourse in Section IV.

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[1] see websites: http://www.powercastco.com/

II. STATE OF THE ART

Let us commence with a crisp survey of the SWIPT literature, followed by the summary of practical transceiver architectures. Owing to the limited number of references allowed, we apologise that only a few of the seminal SWIPT references are cited, while a comprehensive survey will follow in our future work.

A. *Theoretical Studies*

There is a paucity of literature on the current theoretical research advances in SWIPT, which are almost entirely concentrated on the *energy versus capacity* trade-off. The pioneering work of [3] revealed that a non-trivial trade-off exists between the available energy and the achievable capacity for typical channel models, such as the Binary Symmetric Channel (BSC) and the Additive White Gaussian Noise (AWGN) channel, indicating that maximizing the information rate is to a degree coupled with maximizing the energy transfer. Indeed, when a wideband fading channel is considered, the authors of [4] confirmed this fundamental trade-off between energy and capacity, where the classic water-filling based power allocation applied across the entire frequency band maximized the attainable information rate, while energy transfer was maximized by transmitting at a single frequency using the total available power, thus reducing the information rate. Similar conclusions were also drawn concerning this fundamental trade-off for narrowband Multiple Input Multiple Output (MIMO) channels [5], where water-filling based power allocation spanning all eigenvalues of the channel-matrix maximizes the information rate. By contrast, the energy transfer is maximized by concentrating all available power in the specific direction corresponding to the maximum eigenvalue. Further research considered various other important channel models, such as the families of interference channels, multiple access channels, unicast/multicast channels and secrecy channels.

Alongside those theoretical results, practical receiver architectures facilitating SWIPT were proposed in [7]. In addition to the widely investigated *one-way* SWIPT focusing on receiver architectures, the scope of SWIPT may also be further expanded to *two-way* SWIPT [8], where a pair of nodes interactively communicates and exchanges power. A related topic is the so-called wireless-powered communications [9], where the transmitter conveys power to the receiver, which is then converted to Direct Current (DC) power and reused for the destination's information transmission in the reverse direction. Finally, a range of other treatises considered diverse energy-transfer-aided systems, such as multi-carrier systems, relay-assisted arrangements, cognitive-radio settings and beamforming-aided systems.

B. *Practical Architectures*

Most of the above information theoretical insights were drawn under the assumption that the information can be retrieved at the same time, when the power is received. However, practical transceivers may not readily support this operation. From an implementational point of view, there are three types of transceiver architectures that may be capable of supporting a SWIPT system as shown in Fig 1.

1) Building Blocks: Before proceeding to our detailed elaborations, we first introduce the concept of power transfer tunnel and information transfer tunnel, as seen in Fig 1a. The *power transfer tunnel* typically consists of a rectifier used for converting the received Radio Frequency (RF) power to DC power, which is followed by a (multi-stage) DC to DC booster. Subsequently the power is stored in the battery. Note that from a pure power transfer point of view, the antennas and the rectifier are jointly known as a rectenna. On the other hand, the *information transfer tunnel* typically consists of a Base-Band (BB) Digital Signal Processing (DSP) module invoked after the RF-to-BB down conversion process at the front-end. More explicitly, there are various RF-to-BB designs, which typically include filters, mixers, amplifiers and Analogue to Digital (A/D) converters etc.

2) Different EM Waves: The first type of architectures supports SWIPT system by employing two different EM waves for information transfer and power transfer, respectively [10]. The most straightforward option is the *parallel independent* architecture seen in Fig 1a, where two transmitter and receiver pairs are applied in parallel using two well isolated EM waves, naturally one for power transfer and one for information transfer. The two interfaces may be independently operated or coordinated by a controller. By contrast, an amalgamated option is constituted by the *parallel combined* architecture seen in Fig 1b, where the power transfer process is incorporated into the information transfer process by mixing the low-frequency carrier used for power transfer with the high-frequency carrier invoked for information transfer. Following the down-conversion operation of the superheterodyne receiver, the low frequency carrier shifted to DC by the rectifier is subsequently entered into the power transfer tunnel, while the high frequency carrier shifted to the Intermediate Frequency (IF) is further processed before entering it into the information transfer tunnel.

3) Identical EM Waves: The second type of architectures facilitates SWIPT by relying on a single EM wave for information transfer and power transfer. Practical receivers facilitating SWIPT may be operated in two different modes [5], namely either on a *time-switching* basis or on a *power-splitting* basis, as seen in Fig 1c. To be more specific, in the time-switching mode, the receiver alternatively and opportunistically activates the information transfer tunnel and the power transfer tunnel. On the other hand, in the power-splitting mode, a certain portion of the received power is used for powering the receiver, while the remaining received power is used for retrieving information. Note that the time-switching receiver may be viewed as a special case of the power-splitting receiver when the splitting ratio is either one or zero. When channel information is available at the transmitter, the two operating modes may be further optimally configured.

4) Varshney's Concept: Apart from the above-mentioned architectures, the more beneficial fully integrated information and power transfer philosophy can be used as the ultimate objective in the spirit of Varshney's seminal concept [3], which proposed that energy and information transfer should be innately inter-linked. In this light, the *integrated* architecture of [7] was proposed, which is seen in Fig 1d, where the rectifier employed for power transfer at the receiver additionally acts also as the front-end for RF-to-BB down-conversion. The resultant DC signal is then passed both to the energy storage and to the information retrieval blocks in either a switching or a splitting approach. In order to enable SWIPT using an integrated receiver, a specifically designed modulation-specific energy is required, which relies on the Varshney's concept stating that ”information is patterned matter energy”. Finally, it is also worthnoting that the underlying difference between the approach of Fig 1c and of Fig 1d is that the former requires both a rectifier and RF-to-BB down-conversion, while the latter only necessitates a rectifier.

III. DESIGN ASPECTS AND POTENTIAL SOLUTIONS

Let us now focus our attention on exploiting the identical EM waves and hence the architectures discussed in Sections II-B3 and II-B4, whilst considering the important aspects in designing the SWIPT system from both a link level as well as from a system level perspective, along with a variety of promising solutions and potential research ideas.

A. Link-level Design Aspects

There are several important building blocks deserve special attention in the link-level design of SWIPT. These include the efficient and compact design of rectennas, the smart design of battery management and the powerful as well as robust design of BB signal processing algorithms. Let us now elaborate on the last point from a communications perspective in the context of a SWIPT system, while referring the readers for cross-disciplinary details on rectenna design and battery management in [11]. More particularly, when taking into account the characteristics of a SWIPT system, three physical layer components have to be discussed in more detail, with the design aspects of multi-antenna aided techniques being the most critical ones for the practical exploitation of SWIPT.

1) Multiple Antennas - Key to Practical Applications: There are several constraints that fundamentally limit the development of SWIPT systems. Firstly, owing to the fact that the EM radiation is restricted by both health and safety regulations, the power supplied by the source is typically limited. For example, a macro base-station emits 46 dBm power, while an indoor access-point has a transmit power of 23 dBm. Secondly, the hostile wireless propagation, including path-loss, shadowing and multipath fading, substantially reduces the average received RF power. Thirdly, a state-of-the-art rectenna exhibits a conversion efficiency of about 50% reported say by Powercast, which can only be activated above a certain RF input power level, typically above -15 dBm. As a result, the combined effect of the above facts suggests that SWIPT system is limited to a very *short range*.

To extend the attainable range of SWIPT, multiple antennas are necessary, since they are capable of providing a larger antenna aperture and a higher antenna gain. Practically, to accommodate a large number of antennas in a compact, shirt-pocket-sized communicator, a higher carrier frequency is found to be beneficial in SWIPT system, such as for example the 5.8 GHz band and higher. When equipped with multiple antennas, two different signal processing operations are promising, namely analogue domain *beam-forming* using a phase shifter with/without complex weighting and digital domain *pre-coding*, which may be flexibly designed for satisfying a predefined rate and/or power constraint.

Indeed, beam-forming techniques may be deemed to act as the key for SWIPT systems and most of the open literature is focused on this topic. For example, Xu *et al.* in [12] considered the energy beam-forming concept in the context of a Multiple-Input Single-Output (MISO) downlink system. Furthermore, Park and Clerckx in [13] designed a beam-forming aided solution for a K-user interference-limited system relying on multiple transmitter and receiver pairs, while Li *et al.* in [14] considered a collaborative energy beam-forming design using multiple transmitter and receiver pairs. The beneficial impact of large-scale/massive MIMOs was studied in [15]. Finally, active research also addressed a range of practical aspects, such as only having partial Channel State Information (CSI) relying on a realistic CSI feedback design. Regretfully, these solutions cannot be cited here owing to the limited number of allowable references.

2) Channel Coding - Key to Link Reliability: SWIPT would cause energy depletion that will result into *processing-induced errors* owing to voltage variations in addition to *channel-induced errors* owing to wireless prorogation that only found in conventional wireless communications. To elaborate a bit more, SWIPT receivers are usually considered to be passive or semi-passive, relying upon the received power to drive the receiver circuits. In this scenario, the time-varying operating and channel conditions can result in fluctuations in the received voltage level from time to time. In this occurrence, the propagation delays of the electronic signals within the receiver circuits will be extended and may exceed the period of the clock which synchronises the timing of the circuits. This will result in processing errors, corrupting the data represented by the electronic signals in the receiver circuits. Therefore, inherently *robust* channel coding design is required in order to mitigate both the channel-induced errors as well as the processing-induced errors, which may occur within any of the receiver circuits including the channel coding circuit itself.

The channel coding design in SWIPT must also strike a desirable *energy efficiency balance* between the transmission energy efficiency and processing energy efficiency [16]. This is because channel codes that facilitate a high transmission energy efficiency are typically complex and hence suffer from a low processing energy efficiency. In this context, Fig 2 compares both the transmission-related and the signal-processing-induced energy consumption of a range of different channel codes. In addition, another characteristic of SWIPT systems is their potential *discontinuous operation*, where discontinuous energy and information reception will be observed at the receiver. In this light, the channel coding design should have to tolerate this variability or discontinuity, which would require a powerful short-delay code design. To sum up, in order to holistically design a channel coding scheme for SWIPT systems, both the hardware as well as the algorithmic aspects of channel coding have to be revisited. It is thus envisioned that delay-limited short code design is required for counteracting their potentially discontinuous operations, when taking their energy depletion problems also into account.

3) Modulation - Key to Data Integrity: When the power-splitting receiver architecture of Fig 1c is employed, any conventional modulation scheme may potentially be employed. By contrast, when

Varshney's principle is adopted and the integrated receiver architecture of Fig 1d is employed, energy-conscious modulation schemes would be desired. This is because no explicit RF-to-BB down-conversion chain is used by the integrated receiver of Fig 1d. On the other hand, the rectennas invoked for power conversion at the front-end of the integrated receiver extract only the energy. This is reminiscent of energy harvesting from light, where for example, pillars of silicon are aligned in parallel to the incoming light in order to improve the achievable photon harvesting and a radial PN junction is used for efficiently collecting the carriers. Hence, the intensity modulation, which is routinely used in optical communications is of high interest. A typical example is constituted by the classic on-off keying, where a binary one does carry power while a binary zero does not [8]. At the same time, the specific pattern of power transfer (the particular instance of the appearance of a one) conveys information. Hence, the duality of power and information transfer explicitly manifests itself. A related observation is that variable-length constraint channel coding scheme [17] that generates unequal number of ones and zeros may be found beneficial in satisfying the joint power transfer and information transfer requirements.

Inspired by spatial modulation, a novel generalised modulation scheme conceived for SWIPT was proposed by invoking multiple antennas [18], where information is carried not by the classic radio *waveforms* but by energy *patterns*, as seen in Fig 3. More explicitly, the specific choice of the transmitted pattern energy embeds information into the pattern of the power delivered, which may assume 1) a position-based energy pattern, which is reminiscent of the Pulse Position Modulation (PPM) concept, but invoked in the spatial domain. 2) an intensity-based energy pattern, which is similar to Pulse Amplitude Modulation (PAM), but exclusively relying on positive values. Note that other intensity/pulse based modulation schemes, such as Pulse Width Modulation (PWM) and Pulse Interval Modulation (PIM), may also be beneficially combined with the concept of energy pattern based transmission conceived for an integrated receiver. Finally, the rate versus energy trade-off of the advocated energy pattern aided SWIPT is illustrated in Fig 4.

B. System-level Design Aspects

The above-mentioned key components are critical enablers in the development of SWIPT at the link level for transmission from a single point to a single point. Let us now focus our attention on the system-level design of SWIPT.

1) Beyond Point-to-Point Transmission: We commence our discussions with the widely considered scenario of a single-cell, multi-user SWIPT system. A typical observation in this scenario is the *coverage difference* between the power-transfer zone and information-transfer zone [9]. This is due to the different operational point of the power transfer functionality and of the information transfer functionality, where the former typically operates above say -15 dBm, while the latter only has to maintain a certain average received Signal to Noise Ratio (SNR). In a noise-limited system, the noise floor is typically lower than -100 dBm (including both the thermal noise and processing noise). Then the requirement of a 10 dB average received SNR would result into an operational point of -90 dBm. Hence again, this disparity translates into a substantially different radius for the power-transfer zone and for the information-transfer zone.

A plausible observation in this scenario is that there is a potentially imminent benefit owing to having a *multi-user gain*, when compared to the point-to-point case. This is because the existence of multiple users provides scheduling opportunities for ensuing that the power supplied at the source would not be wasted by the users experiencing severely faded channels. As a result, in a single-cell multi-user SWIPT system, a challenge arises when the transmitter has to optimally allocate its resources and then has to efficiently schedule its information as well as its power transfer action associated with the most appropriate multi-antenna signalling methods. This will become more insightful if a specific Quality of Service (QoS) metric, such as the delay, is also taken into account.

2) The Pros and Cons of Interference: When considering a multi-cell multi-user SWIPT system, a conflicting view of the interference emerges, since interference is desirable from a power transfer point of view, but it is unwanted from an information transfer point of view. Intelligently harnessing the interference would reshape the above-mentioned coverage gap between the power-transfer zone and the information-transfer zone. More explicitly, the *proactive* prevention of interference, with the aid of interference avoidance via (fractional) frequency reuse and interference averaging via frequency hopping, may require a radically new design in the context of SWIPT. On the other hand, the *passive* retrospective reduction of interference, such as parallel or serial interference cancellation and interference suppression relying for example on Interference Rejection Combining (IRC) may still be employed. As further advances, the interference may be beneficially turned into a precious source of designed signal energy when the concept of Coordinated Multiple Points (CoMP) transmission is adopted in a multi-cell multi-user SWIPT system [14]. Finally, interference alignment may require further fundamental revisiting of the impact of the power transfer requirements.

A closely coupled topic with interference being the central focus lies in the cognitive model, where in addition to the SWIPT system established over the primary link, the battery of the passive or semi-passive primary receiver may also be charged by the transmissions of the secondary link. As a result, a conventionally harmful secondary transmission becomes potentially useful in the context of a SWIPT system. In this case, the underlying interference model is of paramount importance, where in a pair of primary and secondary links, four potential operation combinations are feasible at the respective receivers of the primary and secondary links, as detailed in [13]. This naturally necessitates further game theoretical and information theoretical insights. Last but not least, there has been emerging work on system-level SWIPT, which relied on the powerful stochastic geometry to draw macroscopic impact [19].

IV. CONCLUSIONS

We introduced the background rationale and motivation of SWIPT systems with the aid of a brief survey and provided a basic architectural summary. We also discussed its practicality by detailing several critical aspects ranging from the link-level to the system-level design. We envision that the dream ”to facilitate and cheapen the transmission of intelligence” by Nikola Tesla would become a reality, with the added benefits of having a substantially reduced carbon footprint, provided that the research community improves both the rectenna and battery design as well as the communications and signal processing techniques.

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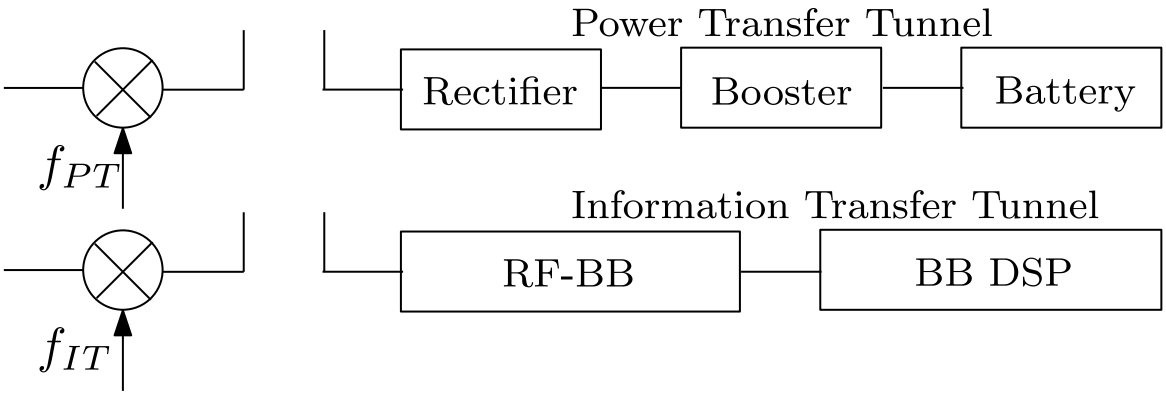
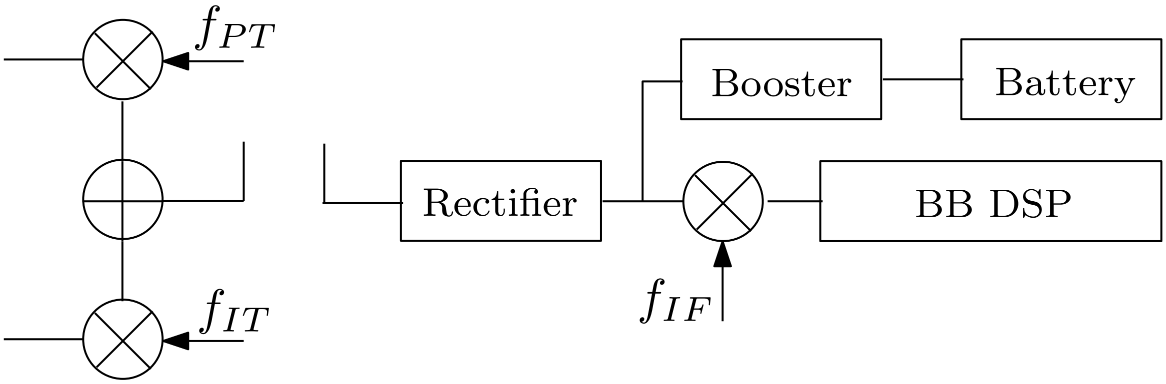
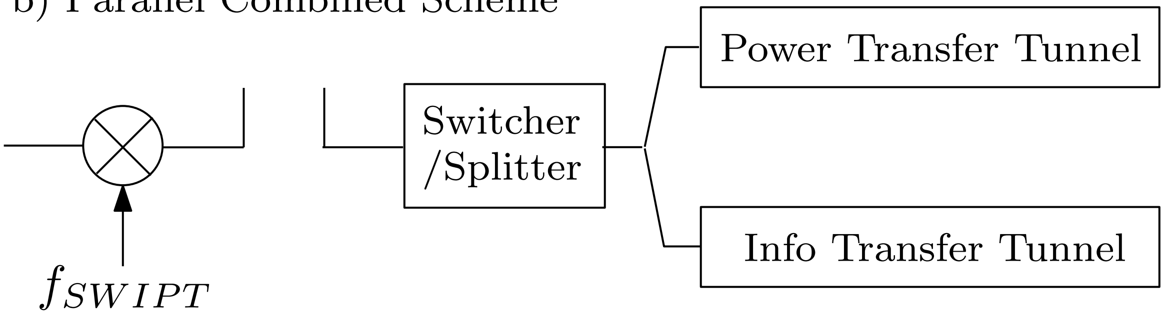


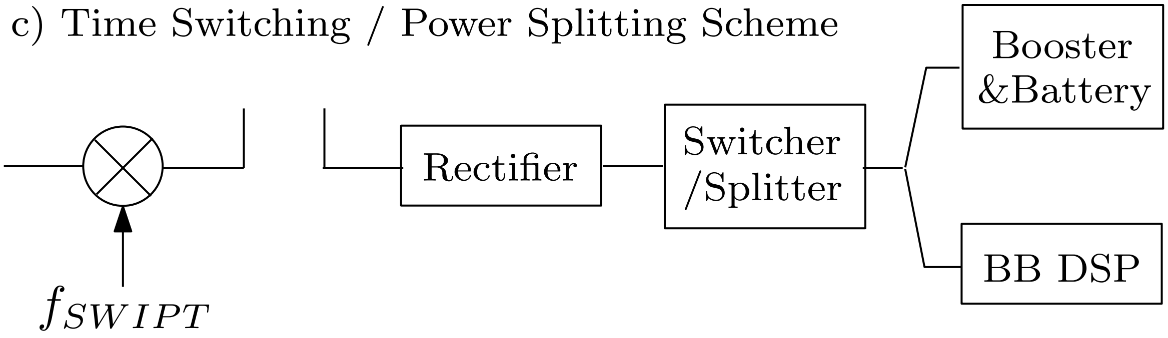
a) Parallel Independent Scheme



b) Parallel Combined Scheme



c) Time Switching / Power Splitting Scheme



d) Integrated Scheme

Fig. 1. Transceiver architectures conceived for SWIPT.

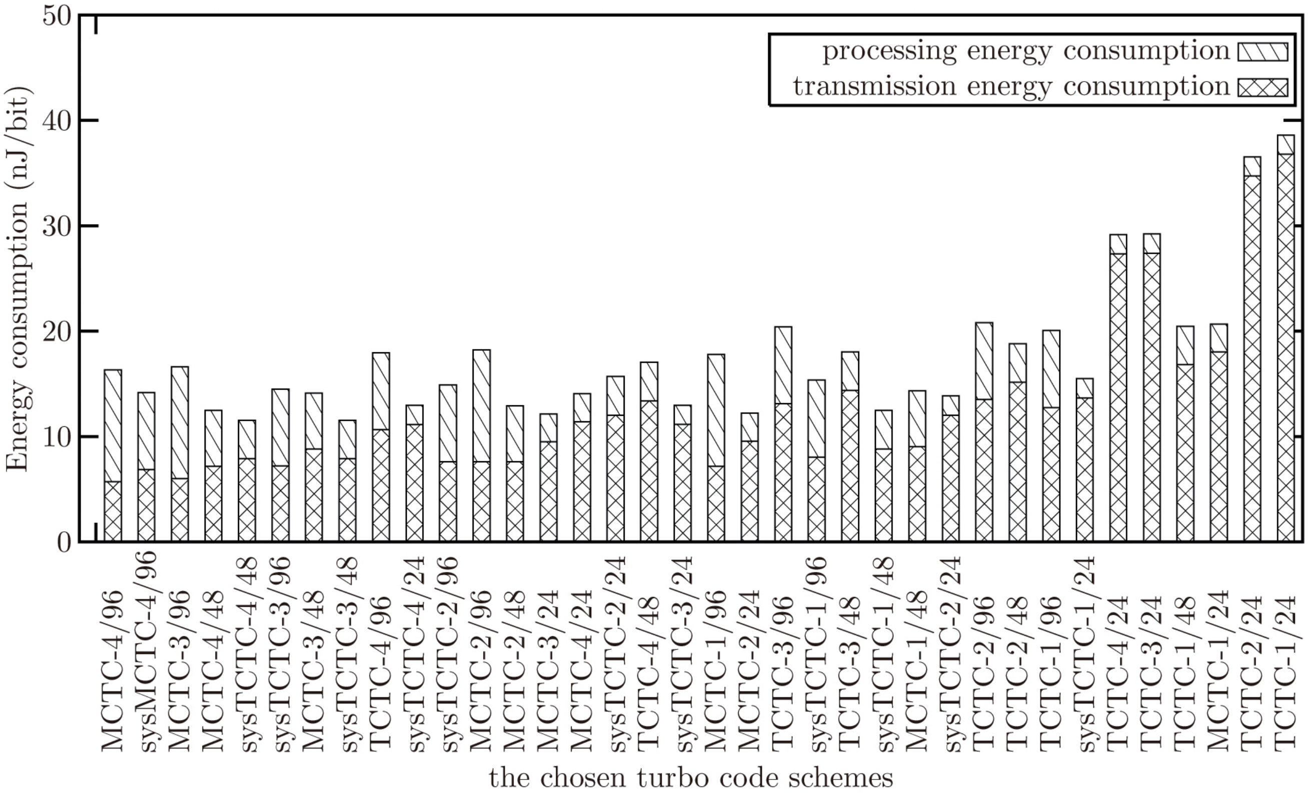


Fig. 2. Transmission energy consumption and processing energy dissipation of different turbo codes at the bit error ratio of 10^{-5}. In this plot, we listed different Twin-Component and Multi-Component Turbo Codes in the format of TCTC-x/c and MCTC-x/c, where 'x' is the shorthand for a particular combination of coding parameters and 'c' is their fixed complexity. More explicitly, sufficiently high transmission energy reserves are required for maintaining an acceptable SNR, while the processing energy consumption encapsulates the energy dissipation imposed by four dominant turbo code components, namely of the datapath, of the controller, of the memory and of the interleaver. This plot clearly exemplifies that jointly considering both power dissipation factors of the channel codes is indeed important in the design of passive/semi-passive receiver. Finally, note that the complexity is given as $2^m * N$, with 'm' being the number of memory elements per component codes and N being the number of BCJR operations with sequential decoder activation order.

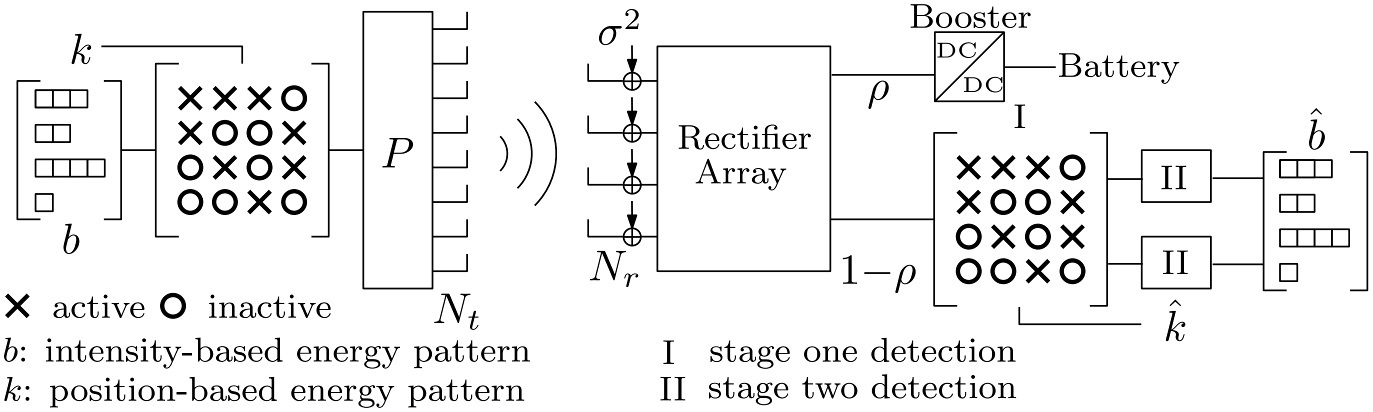


Fig. 3. Energy pattern aided SWIPT with integrated receiver. In this plot, position-based energy patterns are used for activating a particular receive antenna index using an appropriate transmit pre-coding method. The intensity-based energy pattern is generated by mapping the positive PAM symbols onto the activated receive antennas. At the receiver, the rectifier array serves the dual purpose of converting RF power to DC power for power transfer and the RF signal to BB signal for information transfer, which is arranged in two-stages for the sake of extracting the information embedded in the position-based and intensity-based energy patterns.

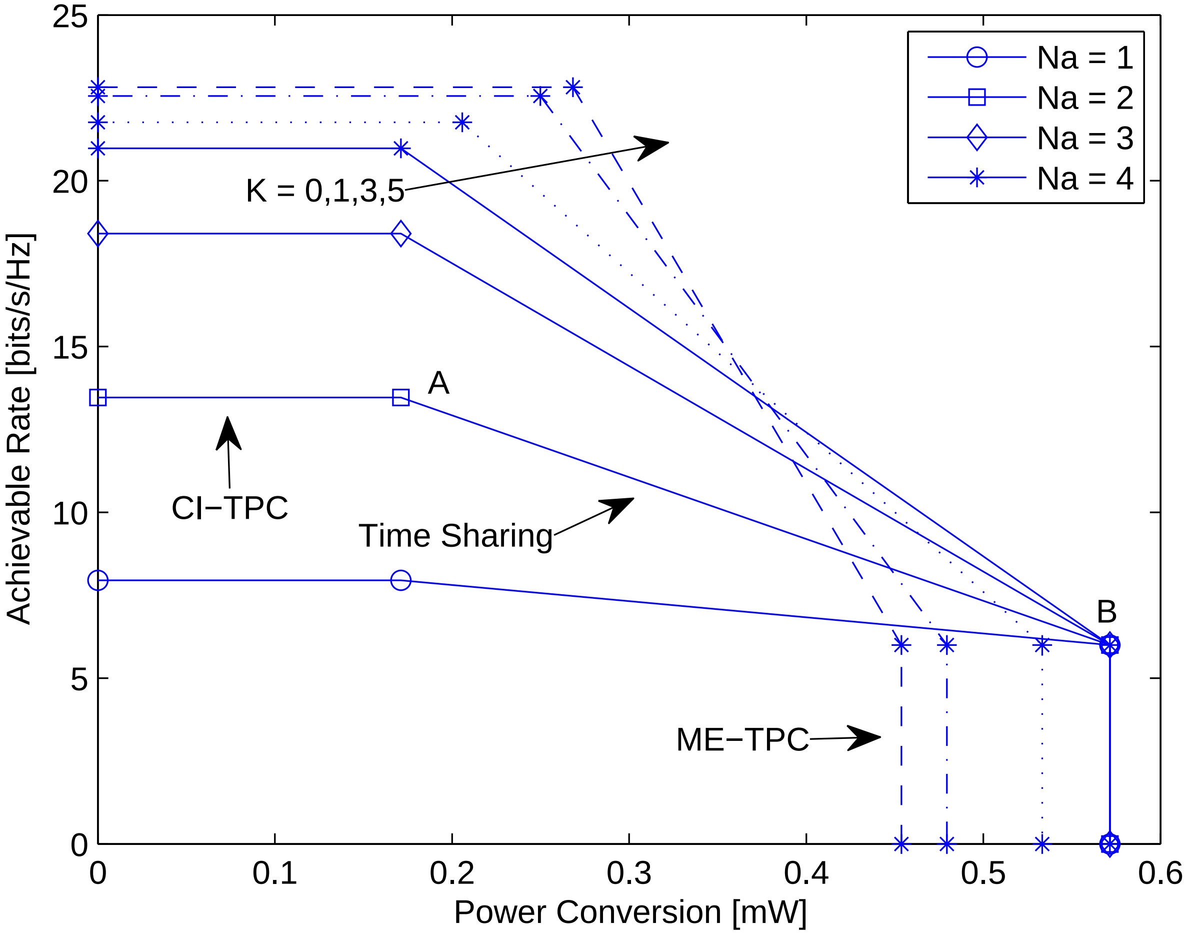


Fig. 4. Trade-offs between the achievable rate and power conversion of a $\{N_t, N_r\} = \{8, 4\}$ energy pattern aided SWIPT system employing different number of activated receive antennas $N_a = [1, 2, 3, 4]$ for position-based energy pattern aided and $M = 64$-ary intensity-based energy patterns assisted transmission. We used Rician fading associated with $K = [0, 1, 3, 5]$ at a transmit power set to $P_t = 30$dBm with the pathloss model of $P_r = P_t A_t A_r (d_0 \lambda_c)^{-\alpha_{pl}}$, where $d_0 = 5$m is the distance between the TA and RA array. Furthermore, λ_c denotes the wavelength corresponding to a carrier frequency of 5.8 GHz, the path-loss exponent is set to $\alpha_{pl} = 4$ and the aperture of the TA and RA is represented by A_t and A_r, respectively, with the per-antenna aperture being set to 1 cm^2. Moreover, both the Channel Inversion (CI) based Transmitter Pre-Coding (TPC) aided arrangement and the Maximum Eigenvalue (ME) based TPC aided arrangement are characterised, where the lines connecting point A and B are achieved by time-sharing between the two TPC methods.