Modulation and Coding Design for Simultaneous Wireless Information and Power Transfer

Jie Hu, Yizhe Zhao, Kun Yang

Abstract—In order to satisfy the power-thirst of the IoT devices and thus extend their lifespan, the radio frequency (RF) signal aided wireless power transfer (WPT) is exploited for remotely charging. Carefully coordinating both the WPT and wireless information transfer (WIT) yields an emerging research trend in simultaneous wireless information and power transfer (SWIPT). However, the SWIPT system designed by assuming Gaussian distributed input signals may suffer from a substantial performance degradation in practice, when the finite alphabetical input is considered. In this article, we will provide a design guide of the coding controlled SWIPT and study the modulation design in both the single-user and multi-user SWIPT systems. We hope that this guide may push the SWIPT a step closer from theory to practice.

Index Terms—Simultaneous Wireless Information and Power Transfer (SWIPT), Wireless Information Transfer (WIT), Wireless Power Transfer (WPT), Coding, Modulation, Finite Alphabet

I. INTRODUCTION

In the imminent Internet of Things (IoT) era, massive number of sensors and IoT devices will be deployed for various applications. These miniature devices are normally powered by embedded batteries. Frequent energy-consuming operations may quickly drain their batteries. Due to its high flexibility and low investment on infrastructure, the carefully controlled wireless power transfer (WPT) relying on the radio frequency (RF) signals [1] can be invoked for remotely charging these low-power devices. Coordinating wireless information transfer (WIT) and WPT in the same RF spectral band thus yields the research of simultaneous wireless information and power transfer (SWIPT) [1]–[6].

With the aid of the SWIPT, the sensors may successfully recover the instruction information from the downlink RF signal emitted by the gateway, while harvesting a portion of the RF signal's energy for powering their own operations [1]. Furthermore, the SWIPT is also suitable to be applied in the two-hop cooperative communication. The transmitter initially transmits the modulated RF signals to the relays. With the aid of the harvest-then-cooperate and the harvest-store-cooperate protocols, a portion of energy carried by the moddulated RF signals can be harvested by the relay stations for powering their cooperative information forwarding to the remote users [2]. The benefit of the wireless powered relay is two-fold: Firstly, no extra energy is consumed by the relay, which encourage the cooperation between users. Secondly, the deployment of the relay stations becomes more flexible, since they do not have to be connected to the power grid.

Inspired by these promising applications, intense efforts have been invested in the SWIPT recently. Chen *et al.* [3] maximised the harvested power by optimally designing the transmit covariance matrix in a point-to-point multiple-input-multiple-output (MIMO) aided SWIPT system. Lv *et al.* [4] proposed an optimal time-domain resource allocation scheme among the multiple receivers for controlling the SWIPT in the downlink and for maximising the sum- and fair-throughput in the uplink. However, either as the constraint [3] or as the objective [4], the attainable WIT throughput is always evaluated by the classic Shannon-Hartely channel capacity, which is achieved by assuming the infinite Gaussian distributed input. By contrast, in any of the practical communication systems, only finite alphabet can be transmitted due to the modulation schemes having limited constellation points and the coding scheme having limited codewords. As a result, the attainable WIT throughput can only be evaluated by the discrete-input-continuous-output mutual information. Therefore, Kim *et al.* [5] firstly studied the rate-energy trade-off in a SWIPT system with equi-probable finite alphabetic input, while Zhu *et al.* further extended their study to a MIMO-SWIPT system [6]. However, the impact of the modulation design on the SWIPT performance is overlooked in [5], [6], especially when a practical WPT receiver is invoked. In another hand, after Varshney analysed the SWIPT from the information theoretical perspective in his seminal work [7], surprisingly, few efforts have been invested in continually exploring the information theoretical limit and in designing the resultant coding design for the SWIPT system.

Fig. 1: The tranceiver architecture with a SWIPT receiver.

Fig. 2: Coding controlled SWIPT. A pair of codewords '10101' and '00100' carry different amount of energy to the WPT receiver for charging its battery. All these codewords are modulated by the OOK.

In this article, we would like to highlight the importance of both the coding and modulation design in the SWIPT system by introducing their theoretical fundamentals and by providing the brief design guides. The main contributions are summarised as follows:

- The popular transceiver architecture of the SWIPT is introduced in Section II.
- A design guide of the coding controlled SWIPT is provided by considering the battery state at the receiver in Section III. The case studies of applying the unary code and the run-length-limited (RLL) code in the SWIPT is provided for illustrating the trade-off between the attainable WIT and WPT performance.
- The impact of the wireless channels and the hardware constraint on the practical modulation design in the SWIPT system is studied for a single user scenario in Section IV, while the principle of the modulation design in multi-user SWIPT system relying on the superposition symbols is also introduced in Section V.
- Open problems concerning the modulation and coding design in the SWIPT system are envisioned in Section VI.

II. TRANSCEIVER ARCHITECTURE

In a SWIPT system, we may have SWIPT users, which extract information and energy from the same RF signals. We may also have dedicated WIT users and WPT users, which receives information and power requested, respectively by exploiting the broadcast nature of the wireless channel.

A. SWIPT Transciever

A typical SWIPT transmitter is illustrated in the top half of Fig.1, which consists of the energy source, the information source, the source and channel encoder, the digital modulator as well as the transmit beamformer. The energy source powers the other functional modules of the transmitter. The power allocated to the digital modulator and the transmit beamformer constitutes the actual transmit power carried by the RF signal.
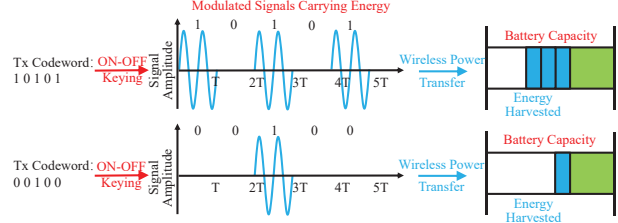
A typical SWIPT receiver is portrayed in the bottom half of Fig.1, which is constituted by the receive beamformer, the signal splitter, the WPT receiver and the WIT receiver. Either the power-splitter or the time-switcher is exploited for splitting the received RF signal into two portions [8]. A portion of the received RF signal flows into the WIT receiver for the demodulation and decoding. The recovered information bits finally arrive at the information destination. The other portion of the received RF signal is converted by a rectifier to the direct current (DC) and it is finally stored in the battery. The rectifier and the battery constitute a typical WPT receiver.

The current research [1]–[6] mainly focus on the design of the front ends of the transceiver by only considering the continuous signals, while largely overlooking the impact of the discrete messages and symbols induced by the coding and modulation of the SWIPT system, as illustrated in Fig.1.

B. Non-Linear Rectifier

As portrayed in Fig.1, a simplified rectifier consists of a diode and a low-pass-filter. The rectifier's non-linearity exhibits in the following perspectives:

- The circuit of the rectifier can only be activated, when the input power of the RF signal is higher than a threshold [9]. This activation threshold is also regarded as the sensitivity of the rectifier.
- The output DC of the rectifier in Fig.1(c) can be formulated as a polynomial of the input RF signal's power [10], which indicates that a higher input power may results in a higher RF-DC conversion efficiency.

These characteristics of the rectifier should be taken into account in the coding and modulation design of the SWIPT system.

III. CODING CONTROLLED SWIPT

A. Fundamental

The landmark work [7] has firstly maximised the mutual information of the discrete-input-

discrete-output channel by optimising the distribution of the discrete input messages, while ensuring that the energy carried by the output messages is higher than a pre-defined threshold. The energy carried by a binary codeword is jointly decided by the following factors:

- The percentage of bit '1' and that of bit '0' in a binary codeword, which is regarded as the structure of the codeword.
- The mapping from the binary bits to the modulated symbols. For example, the binary sequence '1111' is mapped to the symbol carrying the highest energy in the 16-QAM.

In this section, we mainly focus on the design of the codeword structure by adopting the on-off-keying (OOK) based modulation, where only the binary bit '1' carries a single unit of energy, as portrayed in Fig.2.

There is an obvious trade-off between the WPT and the WIT performance. For example, if the channel input always generates an all-one binary sequence, the mutual information is zero, although the maximum energy can be transferred. If the channel input is optimised for only maximising the mutual information, the energy carried by the channel output is a certain value, which might not satisfy the energy request of the receiver.

The basic principle is to generate the codewords with a certain structure in order to simulataneously satisfy the certain requirements of both the WIT and WPT performance. The following coding schemes can be opted for reacing this design target [11]:

- *Compensation Energy Coding*. Dummy binary bits are directly concatenated behind the information bits in order to guarantee that the resultant codeword has a certain percentage of bit '1'. This coding approach has the lowest complexity. However, the dummy bits do not carry any information, which may thus degrade the WIT performance.
- *Inverse Source Coding*. A classic source encoder takes non-equi-probable messages to generate the binary sequence having equi-probable binary bits. By contrast, an inverse source encoder takes equi-probable messages to generate the binary sequence having a certain structure for satisfying the WPT requirement. However, the asynchronization between the encoder and the decoder imposes difficulties in the efficient decoding design.
- *Constraint Coding*. Some constraint coding techniques have degrees of freedom to change the codeword structure for satisfying the WPT requirement. Since they do not include any dummy bits, the WIT performance may not suffer significant degra-

dation. Furthermore, the efficient symbol-level trellis can be adopted for decoding the constraint code.

We will then introduce a pair of typical constraint codes, namely the unary code and the RLL code.

B. Unary Code

The unary encoder maps the j-th input binary sequence onto a j-bit codeword, which has a single bit '0' at the end and all the other bits in front are '1'. For instance, the 4-level unary encoder is capable of encoding four different binary sequences $\{00, 01, 10, 11\}$. The first input sequence '00' is encoded as a codeword '0', while the fourth input sequence '11' is thus encoded as a codeword '1110'. Obviously, different input binary sequence may be encoded as a codeword having different percentage of energy bit '1'. Therefore, the average percentage of energy bit 1 in unary codewords can be adjusted by changing the occurrence probabilities of the input binary sequences, which hence controls the SWIPT performance of the codewords.

C. Run-Length-Limited Code

Another constraint coding technique is the RLL code [12]. A type-0 (d, k)-RLL code has the following constraints on a codeword:

- The runs of bit '0' have a length of d at least between successive bit '1'.
- The runs of bit '0' have a length of k at most between successive bit '1'.

The run-length of bit '0' may be an arbitrary value between d and k. For instance, a type-0 $(1, 3)$ RLL code is capable of generating a binary bit sequence of '10100010010001001 $\cdots$', where the minimum run-length of bit '0' is 1 and its maximum run-length is 3. Obviously, the average percentage of energy bit '1' in type-0 RLL codeword is determined by the occurrence probabilities of the runs of bit '0' having different lengths. For instance, if a type-0 $(1, 3)$ RLL encoder increases the occurrence probability of the runs of bit '0' having a length of 1, the average percentage of energy bit '1' can be thus increased. Therefore, by adjusting the occurrence probabilities of the runs of bit '0' having different lengths, we may control the SWIPT performance of the type-0 RLL codewords. For a type-1 RLL encoder, we should focus on adjusting the occurrence probabilities of the runs of bit '1' having different lengths in order to control its corresponding SWIPT performance.
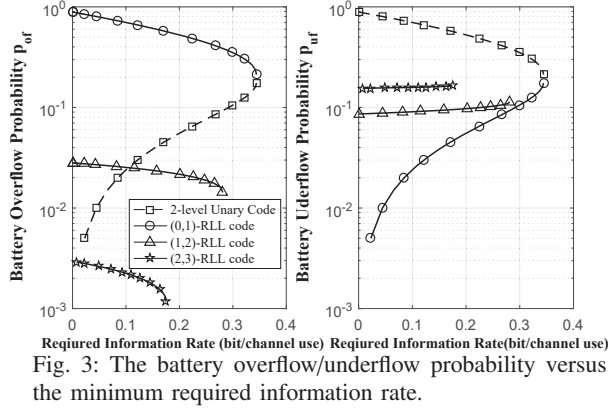
Fig. 3: The battery overflow/underflow probability versus the minimum required information rate.
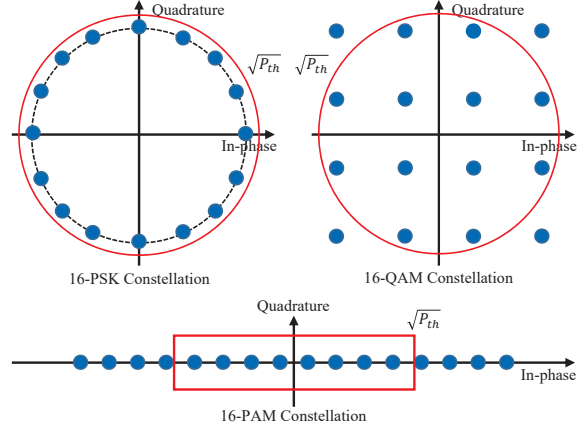

Fig. 4: The input constellations at the WPT receiver. All the constellations have the same average power. The activation threshold of the WPT receiver is denoted as P_{th}.

D. Battery-Aware Design

Since the battery has a finite capacity, the energy carried by a codeword should not be too high in order to avoid the energy waste induced by the battery overflow. By contrast, the energy carried by a codeword should not be too low in order to avoid the energy shortage induced by the battery underflow, which may impair the routine operation of the receiver. The energy stored in the battery of the receiver can be modelled by a discrete queuing process.

By considering the routine energy consumption of the receiver, when a type-0 (or type-1) RLL encoder is adopted for SWIPT, the energy queue is renewed for the duration of a complete run of bit '0' (or bit '1'). The code design then aims for minimising either the battery overflow probability or its underflow probability by optimising the run-length constraints and the occurrence probabilities of the runs of bit '0' (or bit '1') having different lengths, while satisfying the minimum requirement of the information transmission. By contrast, when the unary encoder is adopted, the energy queue is renewed for the duration of a unary codeword. The code design then aims for optimising the level parameter and the occurrence probabilities of the input binary sequences for achieving a satisfactory SWIPT performance.

The SWIPT performance of the RLL code and the unary code is investigated in Fig.3. We assume that the information decoding may not consume any energy carried by the received signal, which is then exploited for charging the battery. For each renewal interval, the receiver consumes a single energy unit with a probability of 0.5. The maximum capacity of the battery is 2 energy unit. A classic Z channel is invoked, where bit '0' can always be successfully received, while bit '1' may be erroneously received as '0' with a probability of 0.2 and it may be correctly received with a probability of 0.8. Observe from Fig.3 that type-0 (0, 1)-RLL code has the highest density of energy bit '1'. Therefore, it may achieve

the highest battery overflow probability and the lowest battery underflow probability. By contrast, 2-level unary code has the highest battery underflow probability, since it has the lowest density of energy bit '1'.

IV. SWIPT WITH MODULATION: SINGLE-USER

A. Fundamental

In a practical communication system, the coded information is then modulated by a specific symbol from a finite alphabet. Therefore, the mutual information of the M-QAM finally converges to a constant, as the transmit power continuously increases. For example, as we increase the transmit power of the modulated RF signal, the mutual information of the 16-QAM converges to 4 bit/channel use, while that of the 256-QAM converges to 8 bit/channel use. Hence, more transmit power should be allocated for the WPT purpose, when the WIT performance converges.

Different modulation schemes exhibit diverse WPT performance, when the non-linearity of the rectifier is considered. We exemplify the received constellations of 16-phase-shift-keying (16-PSK), 16-QAM and 16-pulse-amplitude-modulation (16-PAM) in Fig.4. If the rectifier can only be activated by the received power higher than its activation threshold, which is illustrated by the red circle/rectangle in Fig.4(a), we observe that all the symbols of 16-PSK have been filtered by the rectifier. As a result, the energy carried by the 16-PSK symbols cannot be harvested by the rectifier. In the case of 16-QAM, although 12 symbols are filtered by the rectifier, we still have 4 symbols capable of delivering the energy to the WPT receiver. Furthermore, 16-PAM performs best in terms of the WPT, since it still has 8 symbols capable of delivering the energy. If the rectifier threshold is lower

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than the average power of these modulation schemes, 16-PSK may have the best WPT performance. Furthermore, a higher order modulation scheme has a better WPT performance, since it has more symbols carrying higher energy. Note that when we consider the non-linear RF-DC conversion efficiency of Section II-B, the modulation schemes may exhibit a similar trend in terms of the WPT performance, since a higher input power may result in a higher RF-DC conversion efficiency.

Furthermore, the 'adverse' effect of the wireless channel on the WIT may actually improve the WPT performance. If the scattering of a channel becomes more severe, the multi-path propagation may have a chance to constructively strengthen the signal at the receiver. As a result, the WPT performance can be improved. Furthermore, additional interference is also capable of improving the WPT performance, although it may impair the WIT performance.

B. MIMO aided Modulation

The beamformer/precoder design of the MIMO-SWIPT system has been studied by considering the discrete-input-continuous-output mutual information with finite alphabet [13], where the spatial multiplexing gain is exploited for realising the SWIPT.

Furthermore, the implementation of multiple antennas is capable of facilitating the modulation in the spatial dimension. A specific antenna (or a subset of antennas) can be activated for transmitting a specific information symbol by exploiting the information driven antenna-switching mechanism, which is regarded as the spatial-modulation (SM) or space-shift-keying (SSK). The difference of the channel response impulse is relied upon for identifying the transmit antenna at the receiver for the demodulation. The SM/SSK may substantially reduce the number of RF chains in order to increase the energy efficiency.

Since the SM/SSK system relies on the activation of limited number of antennas for the WIT, the rest of idle antennas can be exploited for gleaning the energy of the ambient RF signals and recycling the energy transmitted by the activated antennas. As a result, the energy efficiency of the SM/SSK system can be further increased.

Furthermore, when we activate a transmit antenna for transmitting a specific information symbol, we may simultaneously activate an additional antenna for the WPT. Since the activation of the additional antenna may certainly deteriorate the WIT performance, the WPT oriented antenna activation scheme should be carefully designed. For example, the WPT channel should have a huge difference response impulse with the WIT channel. As a result, the

receiver can identify the WIT channel for the demodulation by firstly cancelling the interference from the WPT channel.

C. Hardware Constraint

In order to improve the WPT performance, a high-order modulation scheme has to be adopted. However, it may impose great challenges on both the transmitter and the receiver:

- A high-order modulation scheme normally has a high peak-to-average-power-ratio (PAPR). For example, given the same average power, the PAPR of 256-QAM is $\frac{25}{17}$ times higher than 16-QAM. The transmitter thus requires a power amplifier having a very large linear region in order to avoid the energy leakage. As a result, the characteristic of the practical power amplifier has to be considered in the modulation design.
- For the demodulation of the high order modulated symbol, the receiver requires accurate channel state information (CSI) for carrying out the coherent detection. In order to avoid the energy consumption in the CSI acquisition, the non-coherent detection based differential modulation [14] can be adopted by the IoT devices in the SWIPT system. However, the differential modulation may sacrifice both the WIT and WPT performance to some extent, since high order differential modulation is still a technical blank in the literature.

Furthermore, when we have to pack a large number of antennas in a limited area, the following pair of hardware constraints has to be considered:

- Uncorrelated spacing among the large number of antennas cannot be guaranteed in a practical system. The modulated symbols can be further constructively combined by exploiting the antenna correlation both at the transmitter and at the receiver. By considering the non-linearity of the rectifier, high antenna correlation may result in a high WPT performance. The antenna correlation should also be considered in the SM/SSK-MIMO aided SWIPT system.
- As the number of antennas becomes large, it is impossible for feeding each antenna with a single RF chain. As a result, we may process the modulated symbols sequentially in the digital domain and in the analog domain, before they finally transmitted by antennas. By optimising this hybrid beamformer, we may maximise the discrete-input-continuous-output mutual information, while ensuring the required WPT performance.
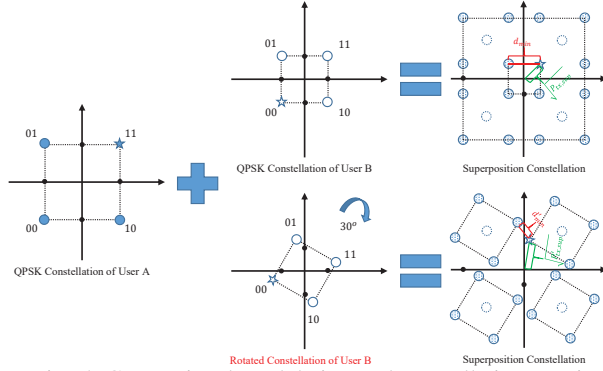
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Fig. 5: Conventional modulation and constellation rotation based modulation for the SWIPT. The symbols requested by the WIT user pair are denoted by the stars. The Euclidean distance between the superposition symbol and the origin is the square root of the actual transmit power.

V. SWIPT With Modulation: Multi-User

A. Superposition Symbol

In order to further improve the spectral efficiency, the symbols requested by multiple users may be superimposed with each other in the same resource block. For example, in the power-domain non-orthogonal-multiple-access (NOMA), the symbols destined to different users are differentiated by their transmit power. Then, the superposition symbol can be demodulated by exploiting the successive-interference-cancellation (SIC). In the sparse-code-multiple-access (SCMA), a symbol is decomposed for modulating onto different sub-carriers. The reconstructed superposition symbol on a specific sub-carrier can be demodulated by the message-passing-algorithm. In the network coded cooperative network, the symbols of different users are superimposed at the hub, which is then broadcast to the users and demodulated. The energy carried by the superposition symbols can be harvested by WPT users due to the broadcast nature of wireless channels.

In all the above-mentioned scenarios, we should constructively superimpose the symbols destined to different WIT users in order to achieve the required WPT performance of the WPT users in the SWIPT system. In the following example, we consider a pair of dedicated WIT users and a single WPT user.

B. Constellation Rotation

In the conventional signal superposition, as exemplified in the top half of Fig.5, the symbols requested by this WIT user pair are destructively combined. The resultant superposition symbol suffers from a substantial energy loss, when compared to the original symbols. The WPT performance is thus significantly degraded. If we rotate the WIT users' constellation for a certain angle, as exemplified in the bottom half of Fig.5, the energy carried by the superposition symbol can be increased in order to satisfy the WPT requirement. However, the constellation rotation may result in the reduction of the minimum Euclidean distance between adjacent superposition symbols, as portrayed in Fig.5, which may deteriorate the WIT performance. An optimal constellation rotation angle should be chosen in order to achieve a balance between the WPT and the WIT performance [15].

The optimal scheme is to design the constellation rotation angles for every pair of symbols requested by WIT User A and B. However, this may impose unaffordable control overhead on the system, since the WIT users have to acquire the knowledge of the rotation angles for demodulating the superposition symbol. In order to reduce the control overhead, the constellation rotation angles can be designed for a pair of symbol blocks requested by WIT Users A and B, respectively, which are constituted by the same length of symbols. As a result, all the symbols in the block requested by WIT user A are rotated by an identical angle, while those in the block requested by WIT user B are rotated by another identical angle. After the rotation, the symbols in these blocks are superimposed pairwise. Therefore, a new symbol block consisting of the superposition symbols is generated and broadcasted in the wireless channel. The constellation rotation angles should be optimised in order to maximise the total power carried by the superposition symbol block, while satisfying a specific WIT constraint. For example, if the maximum likelihood based multi-user detector is invoked by the WIT users, the minimum Euclidean distance of the superposition constellation after the optimal rotation should be higher than a predefined threshold.

C. Comparison

We demonstrate in Fig.6 that our constellation-rotation aided modulation design outperforms its conventional counterpart in terms of the WPT performance in most cases, where the classic AWGN channels having the path loss of 30 dB are invoked for all the users. Moreover, the average transmit power for WIT User A's and WIT User B's transmissions are 1 Watt and 0.1 Watt, respectively. The symbol duration is 10^{-6} second. Specifically, when the activation threshold P_{th} of the rectifier is 1.2 mW, our constellation rotation aided 4-QAM (QPSK) performs worse than the conventional approach. This is because the constellation rotation may produce more low-power symbols, which cannot activate the rectifier. Hence, the WPT performance is degraded. Furthermore, when we increase the
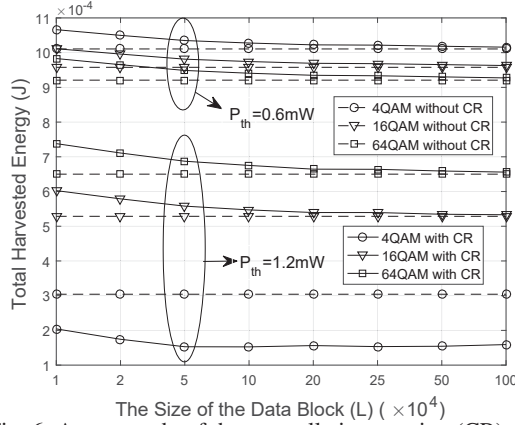
Fig. 6: A case study of the constellation rotation (CR) aided modulation desgin in a SWIPT system having a pair of WIT users and a single WPT user.

size of the symbol block, observe from Fig.6 that the WPT performance of the constellation-rotation aided scheme reduces. This reminds us that we should also strike a trade-off between the control signalling overhead and the attainable system performance. The performance gap between the different-order modulation schemes can be explained in a similar way as we have done in Section IV-A.

VI. FUTURE CHALLENGES AND CONCLUSIONS

The following open problems still need our further investigation:

Concatenated Code: A concatenated encoder consisting of a source encoder, channel encoder and an *energy encoder* should be carefully designed, while a powerful iterative decoder is also required for processing the sophisticated concatenated codewords.

Coded Modulation: The bit-to-symbol mapping from the binary bits to the modulated symbols has to be designed by jointly considering the codeword structure and the modulation characteristic in order to satisfy both the WIT and WPT requirements.

Adaptive Modulation: In order to exploit the distinctive WPT and WIT features of a specific modulation scheme, we should design an adaptive modulation scheme by considering the wireless channel characteristics, the non-linear rectifier and the diverse SWIPT requirements.

This article aims for introducing the fundamental of the coding controlled SWIPT and the modulation design of the signal-user and multi-user SWITP system and for inspiring more endeavour invested in this promising topic.

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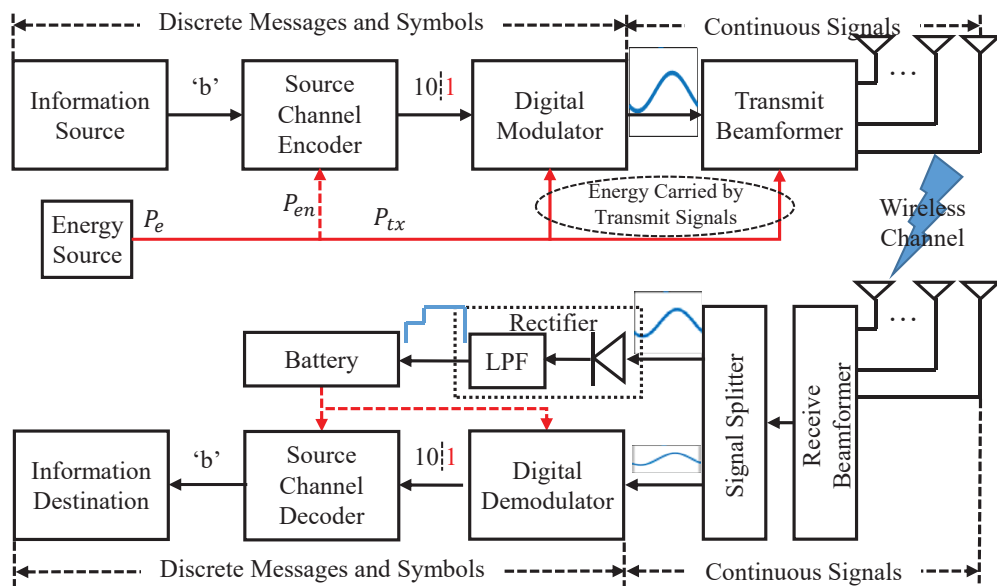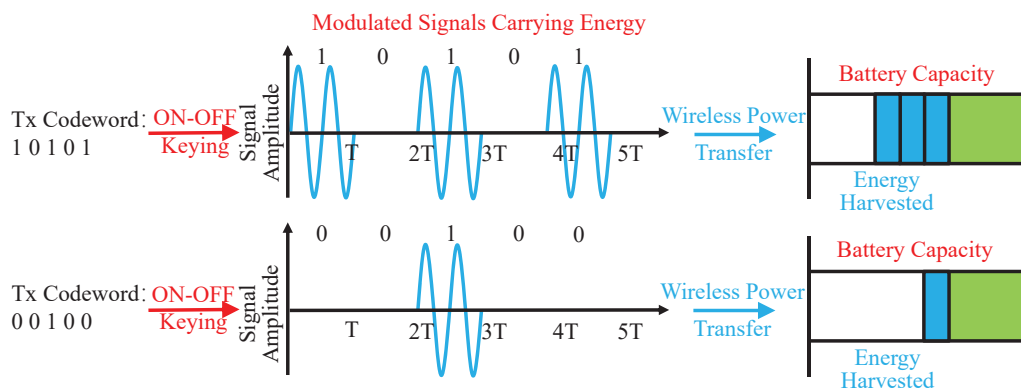
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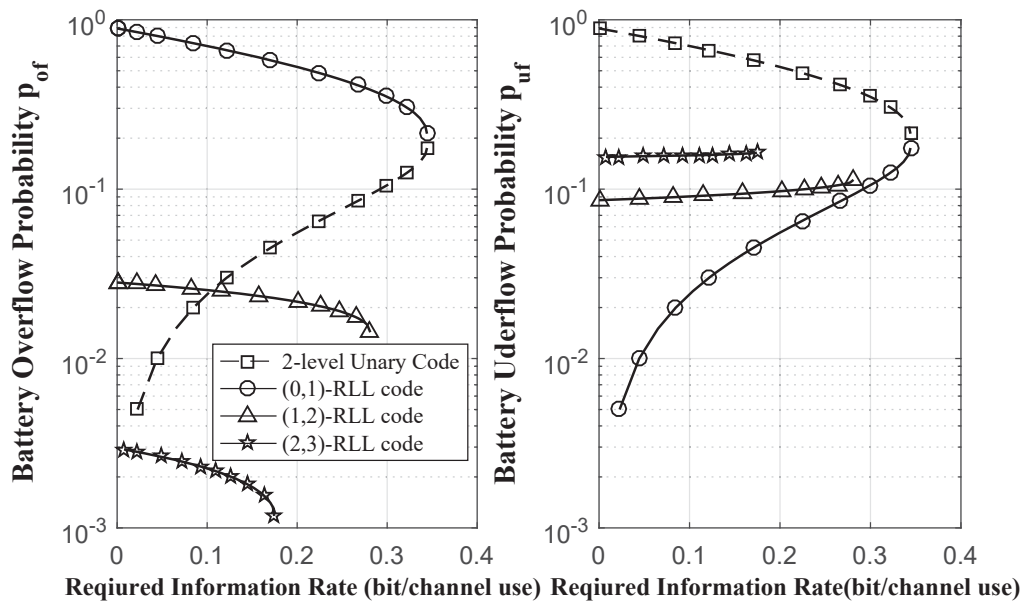
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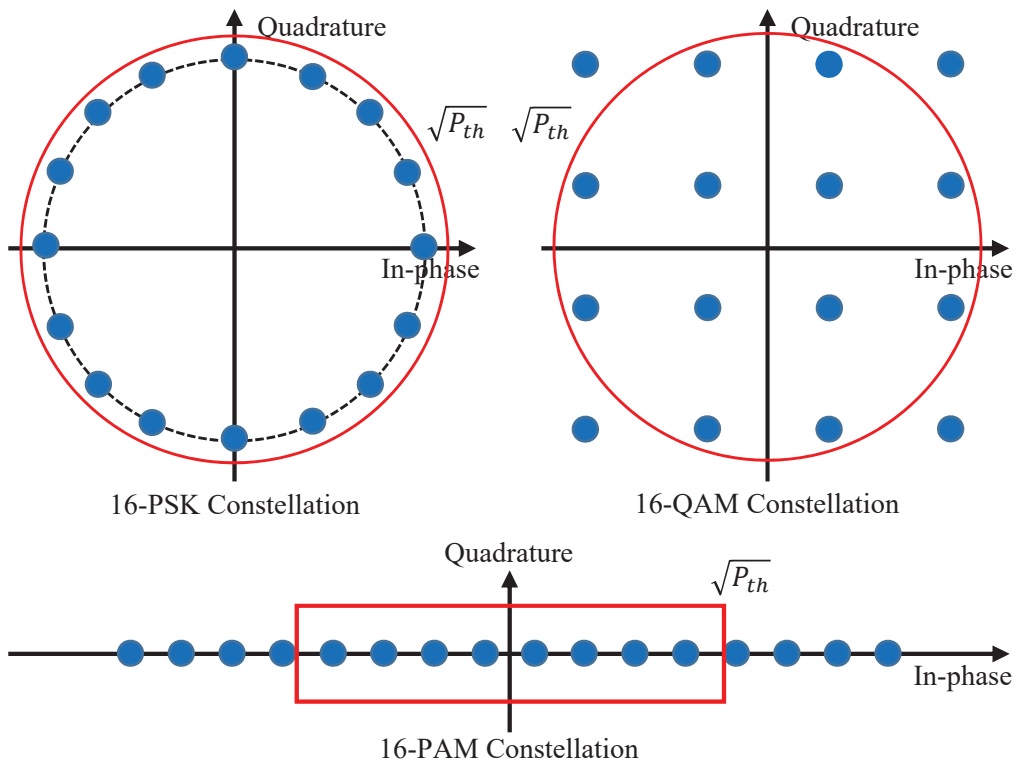
Fig. 4: The input constellations at the WPT receiver. All the constellations have the same average power. The activation threshold of the WPT receiver is denoted as P_{th}.
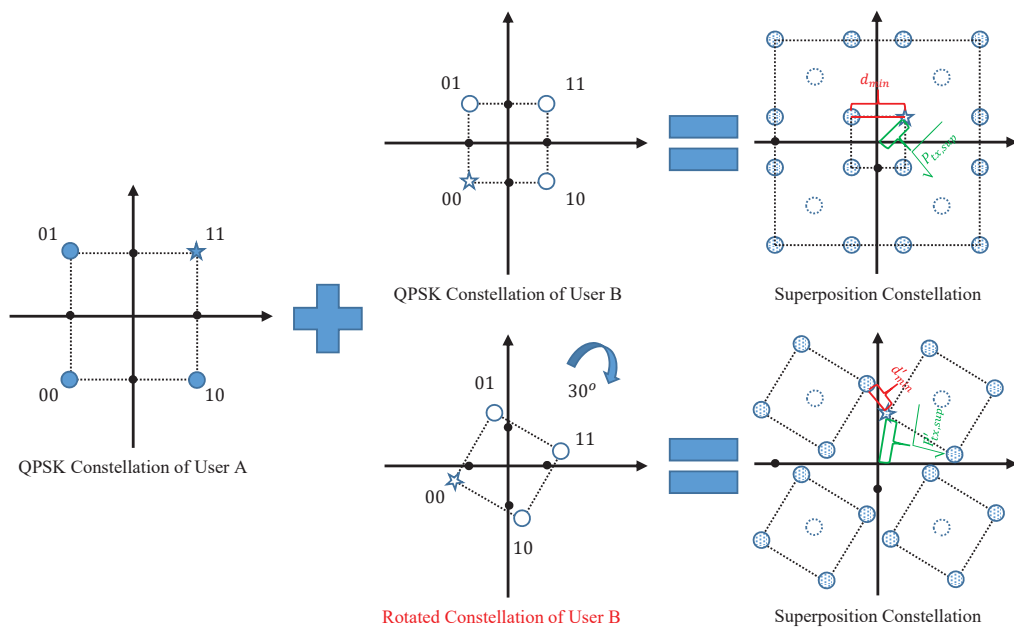
Fig. 5: Conventional modulation and constellation rotation based modulation for the SWIPT. The symbols requested by the WIT user pair are denoted by the stars. The Euclidean distance between the superposition symbol and the origin is the square root of the actual transmit power.
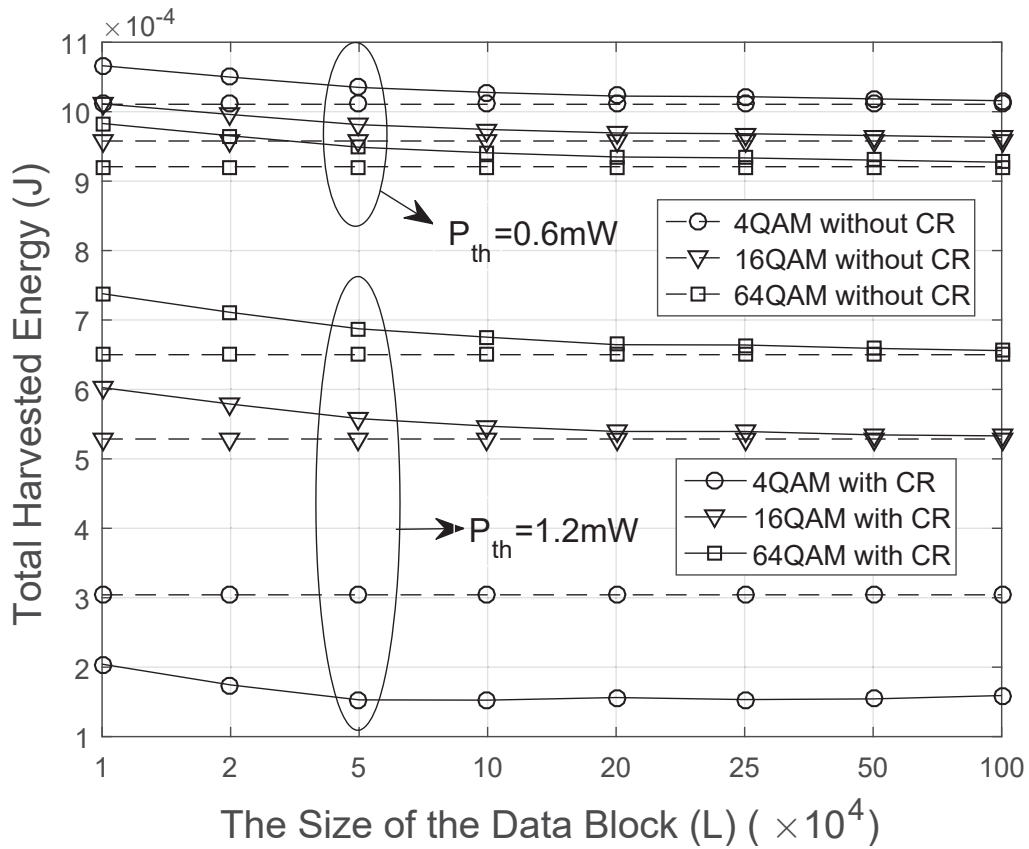
Fig. 6: A case study of the constellation rotation (CR) aided modulation desgin in a SWIPT system having a pair of WIT users and a single WPT user.