

# Enhancing Wireless Information and Power Transfer by Exploiting Multi-Antenna Techniques

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## Abstract

This paper reviews emerging wireless information and power transfer (WIPT) technique with an emphasis on its performance enhancement employing multi-antenna techniques. Compared to traditional wireless information transmission, WIPT faces numerous challenges. First, it is more susceptible to channel fading and path loss, resulting in a much shorter power transfer distance. Second, it gives rise to the issue on how to balance spectral efficiency for information transmission and energy efficiency for power transfer in order to obtain an optimal tradeoff. Third, there exists a security issue for information transmission in order to improve power transfer efficiency. In this context, multi-antenna techniques, e.g., energy beamforming, are introduced to solve these problems by exploiting spatial degree of freedom. This article provides a tutorial on various aspects of multi-antenna based WIPT techniques, with a focus on tackling the challenges by parameter optimization and protocol design. In particular, we investigate the WIPT tradeoffs based on two typical multi-antenna techniques, namely limited feedback multi-antenna technique for short-distance transfer and large-scale multiple-input multiple-output (LS-MIMO, also known as massive MIMO) technique for long-distance transfer. Finally, simulation results validate the effectiveness of the proposed schemes.

## Index Terms

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Wireless information and power transfer; multi-antenna technique; limited feedback; LS-MIMO; transfer tradeoff.

## I. INTRODUCTION

Wireless power transfer has attracted a lot of attention in wireless research community, as it can effectively prolong the lifetime of a power-limited network in a relative simple way, especially under some extreme conditions, such as battle-field, underwater, and body areas networks [1]. For example, in medical care applications, devices implanted in body send information to outside receiver with harvested power from the outside power source. Recently, wireless power information is proposed for cellular systems, to provide mobiles practically infinitely long battery lives and eliminate the need of power cords and chargers. The radio frequency (RF) signal based wireless power transfer attracts considerable attention in both academia and industry due to the following two reasons [2] [3]. First, it is a controllable and deterministic power transfer method. For example, it is possible to flexibly increase transmit power to enhance receive quality. Second, information and power can be simultaneously transferred in a form of RF signal. Then, the communications can be supported without external power sources.

In comparison with conventional wireless information transmission, wireless information and power transfer (WIPT) exhibits both similarities and differences. On one hand, both of them suffer from channel fading and path loss, resulting in performance loss. In particular, power transfer distance may be relatively short, since power harvesting is more sensitive than information decoding [4]. Therefore, it is necessary to effectively combat the fading effects, so as to improve the efficiency and distance of power transfer. For traditional wireless information transmission, multi-antenna technique is a powerful way to enhance the performance over fading channels. Through spatial beamforming, multi-antenna techniques can adapt the transmit signal to channel states, so that channel fading can be harnessed to improve the performance. Similarly, for wireless power transfer, multi-antenna technique can also be used to align the RF signal to a power receiver, thus improving the energy efficiency. Therefore, it makes sense to exploit the benefits of multi-antenna technique to enhance the performance of WIPT. On the other hand, WIPT has two performance metrics, namely spectral efficiency for information transmission and energy

efficiency for power transfer. In general, the two metrics are inconsistent and even contradictory, since information and power compete for the same RF signal and resources. Fortunately, it is convenient for multi-antenna techniques to achieve a good tradeoff between the spectral and energy efficiencies by designing appropriate spatial beams for information and power transfer, respectively [5]. More importantly, multi-antenna techniques may concurrently support multiple streams of information and power transfer, and thus the efficiencies are improved significantly.

To exploit the benefits of multi-antenna techniques for WIPT, the transmitter requires full or partial channel state information (CSI), and then both information and power are transferred adaptively to the channel conditions. Specifically, based on the CSI, a transmitter selects the optimal transmit parameters, i.e. transmit beam, transmit power, and accessing users in order to maximize the efficiencies over fading channels. In [6], an optimal multiuser WIPT system was designed, assuming that full CSI is available at the transmitter. However, in multi-antenna systems, it is a nontrivial task to obtain instantaneous CSI at the transmitter, since the channel is a multi-dimensional time-varying random matrix. Generally, according to different duplex modes, there are two CSI acquisition methods in multi-antenna systems [7]. In frequency division duplex (FDD) systems, the CSI is usually conveyed from the information and power receivers to the transmitter by making use of quantization codebooks, so that the transmitter can obtain partial CSI. Note that a larger codebook size leads to more accurate CSI, but also increases feedback overheads. Therefore, it is possible to improve the efficiencies by increasing the feedback amount. On the other hand, the CSI in time division duplex (TDD) systems can be estimated at a transmitter, directly making use of channel reciprocity. Compared to the CSI feedback in FDD systems, CSI estimation in TDD systems saves the feedback resource, but may suffer from a performance loss due to transceiver hardware impairment. To solve the problem, robust beamforming for WIPT was proposed in [8] to guarantee high efficiencies even with imperfect CSI. Moreover, CSI can also be used to construct transmit beams. However, with respect to the beamforming based on instantaneous CSI, the one based on estimated CSI suffers an obvious performance degradation. Thus, adaptive multi-antenna transmission techniques via CSI feedback or estimation are effective ways to enhance performance for WIPT over fading channels.

For multi-antenna based WIPT techniques, there are a number of transmission frameworks proposed in the literature. First, for multi-antenna techniques, there are several different forms. For example, according to the number of antennas, there are traditional multi-antenna techniques

and large-scale multiple-input multiple-output (LS-MIMO) techniques. Additionally, according to the number of accessing users, we have single-user and multi-user transmission techniques. Second, as mentioned earlier, there are two different CSI achievement methods, namely CSI feedback and CSI estimation. Third, according to the transmission protocols, WIPT can also be classified into two cases. In the first case, information and power are transferred simultaneously, namely simultaneous wireless information and power transfer (SWIPT) [9]. In the second case, power is first transferred, and then the harvested power is used to send information, namely wireless powered communication (WPC) or energy harvesting communication (EHC) [10]. Thus, combining the above three schemes, multi-antenna based WIPT technique has a variety of forms, which are applicable to fit to different scenarios. In this article, we intend to investigate various issues on multi-antenna based WIPT technique from both theoretical and design perspectives. Especially, we analyze parameter optimization and protocol design for various multi-antenna based WIPT techniques. To facilitate understanding, we use traditional multi-antenna technique and LS-MIMO technique based WIPTs as two typical examples to instantiate the wireless information and power transfer tradeoff, and analyze the effect of CSI accuracy and the number of antennas on the tradeoff.

The rest of this article can be outlined as follows. We give an introduction of various multi-antenna based WIPT techniques, and then highlight the parameter optimization and protocol design in Section II. A discussion and comparison of two typical multi-antenna techniques for WIPT are given in Section III. Simulation results are illustrated in Section IV to verify the tradeoff performance of the two typical multi-antenna based WIPT techniques, followed by the conclusions and discussions on several open issues in Section V.

## II. MULTI-ANTENNA BASED WIPT TECHNIQUE

WPT is not a new technology, although it regains considerable interests recently. It was developed more than a century ago and its feasibility has been verified by many practical experiments. At the end of the 19th century, Nikola Tesla carried out the first WPT experiment, which tried to transmit approximately 300 KW power via 150 KHz radio waves. In the 1960s, William C. Brown restarted WPT experiments with high-efficiency microwave technology, and the efficiency reached to 50% at an output power of 4W DC. After the 1980s, many experiments

were carried out in Japan and the United States. In the 2000s, advances in microwave technologies pushed WPT back into consideration for wireless communications. Despite these advances, there are many challenging issues that remain to be open for WIPT. It is because that both information and power are carried by RF signals over wireless media, and they may suffer from attenuation, noise, interference, and interception. Thus, to effectively implement WIPT and evaluate the performance, several fundamental metrics of interest are introduced as follows:

- 1) Transfer efficiency: RF signal will decay due to channel fading caused by reflection, scattering, and refraction in propagation processes. Thus, the received signal may be very weak, making it difficult to recover transmit signal or harvest the signal energy. The problem becomes more prominent for wireless power transfer, since a power receiver is more sensitive to the magnitude of RF signal. Hence, it is necessary to improve the efficiency of WIPT over wireless channels.
- 2) Transfer distance: The attenuation of RF signal is an increasing function of transfer distance. To guarantee a viable received power, wireless power transfer has a stringent limitation on transfer distance based on the current state of the art research. With an increasing demand on wireless power transmission, especially wireless powered communications, this limitation has become a major bottleneck in the development of wireless power transfer. Thus, it is imperative to increase the effective transfer distance.
- 3) Transfer tradeoff: Limited power, spectrum and time resources are shared by wireless information and power transfer, resulting in the fundamental tradeoffs between the two. For example, in the SWIPT, the total transmit power is distributed for information and power transfer. While in wireless powered communications, each time slot is divided into information and power transfer durations. To balance the information and power transfer according to application requirements and enhance the overall performance, it is vital to analyze the optimal resource allocation between them.
- 4) Transfer security: Due to the open nature of wireless media, information transmission is apt to be overheard. The security issue is even severer in WIPT because the power receiver is usually placed closer to the transmitter than the information receiver. Traditionally encryption technology cannot fully solve the problem, because it requires a secure channel for exchanging private keys, becoming impractical in infrastructure-less or mobile networks.

In order to realize efficient, reliable, secure, and long-distance WIPT, various advanced technologies have been identified recently, such as cooperative communication, resource allocation, and user scheduling. In particular, multi-antenna technique has a great potential due to its significant performance gain. On one hand, multi-antenna diversity gain can be exploited to combat channel fading as an effort to improve transfer efficiency and increases transfer distance [12]. On the other hand, multi-antenna multiplexing gain can be leveraged to separate information and power transfer in space, so that the latter two metrics, i.e., transfer tradeoff and transfer security, can be realized simultaneously [4]. Let us take a look at a simple example. If the information is transmitted in the null space of the channel for power transfer, then information security can be guaranteed with the help of physical layer security, even the power receiver is very close to the transmitter [4]. Due to these inherent advantages, multi-antenna based WIPT technique is receiving a considerable attention from both academia and industry. In what follows, we give a detail investigation of multi-antenna WIPT. Due to space limitation, we only consider single-hop WIPT. In fact, the multi-hop transmission technology is also a powerful way of enhancing WIPT. For example, relay technology can shorten the transfer distance, and thus improve the performance [13]. The multi-hop cases will be studied in the future. According to the transfer model and protocol, WIPT can be further classified into SWIPT and WPC. Our investigation will cover a thorough case study of these two models and their integration.

#### *A. Simultaneous Wireless Information and Power Transfer*

As the name implies, SWIPT transmits information and power simultaneously. If the transmitter is equipped with multiple antennas, spatial beamforming adapted to the channel states can be used to improve the performance of WIPT. In this case, the information and power receivers can be either combined or separated. Then, there are two subcases for SWIPT with different design principles.

*1) Combined Case:* In this case, a node plays the roles of both information and power receivers, as shown at the left-hand side of Fig. 1. The design of the transmitter is relatively simple. The core step is to perform spatial beamforming based on the CSI obtained through feedback in FDD systems or direct estimation in TDD systems. However, due to the dual roles, the receiver should be designed carefully. Note that the receiver cannot decode the information and harvest the energy simultaneously due to physical constraints. Then, it is required to separate

the information and power transfer by a certain protocol. Currently, there are mainly two protocols, namely time division protocol [5] and power splitting protocol [11]. Specifically, as shown at the right-hand side of Fig. 1, in the time division protocol, each time slot is divided into information and power transfer durations. Then, the roles of the receiver should switch between the two. Otherwise, in the power splitting protocol, the whole received signal is separated into two parts, one for information decoding and the other for power harvesting.

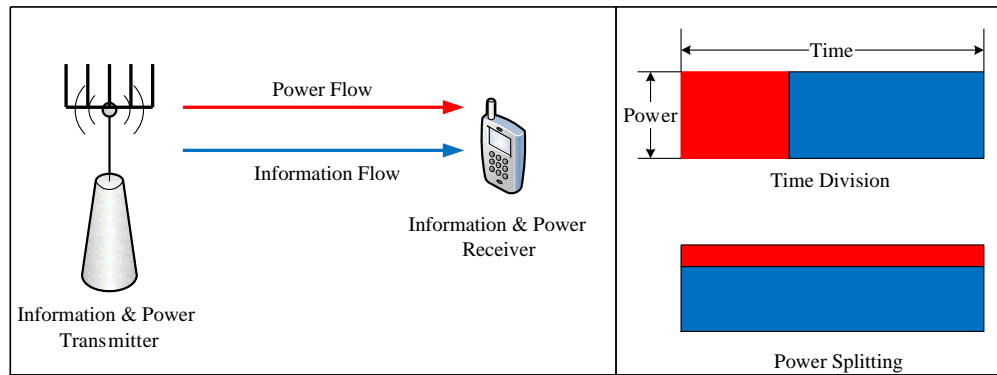


Fig. 1. Model and protocol for combined case of SWIPT.

Comparing the two protocols, we can find that time division requires two RF signal receive modules, since the signals for information decoding and power harvesting are separated at the RF side. Contrastingly, power splitting only needs one RF signal receiver module, and the signals for information decoding and power harvesting are separated at the baseband. Note that there is a balance or tradeoff between the information transmission and power transfer, since the time resource for time division and the power resource for power splitting are constrained and should be allocated to the two tasks according to a certain optimization objective. For example, the WIPT tradeoff can be formulated as an optimization problem of maximizing the information rate subject to a minimum harvested power or maximizing the harvesting power subject to a minimum information rate.

Moreover, there may exist multiple receivers in the combined case. With respect to the single receiver case, there are more challenging problems to be solved. First, the receivers should be scheduled according to the urgency of information and power transfer. However, it is nontrivial to concurrently determine the urgency of information and power transfer. Second, the WIPT tradeoff for each receiver may be distinct. In other words, each receiver may use different durations or



powers for information decoding. Third, the beam design has contrasting goals for information and power transfer. For information transfer, the beams should be designed to mitigate inter-user interference. However, for power transfer, the inter-user interference can increase the received power. Fourth, one or more receivers may be eavesdropper, which gives rise to security problems. A feasible way for multi-receiver SWIPT is to use time division multiplexing access (TDMA), such that each time slot is allocated to only one receiver. Then, the multiple-receiver case is transformed to multiple single-receiver cases combined with receiver scheduling. However, the TDMA protocol may be suboptimal with respect to space division multiplexing access (SDMA) protocol. It is still an open issue to design an optimal multiple access protocol.

2) *Separated Case*: In the case shown in Fig. 2, the information and power receivers are separated in different nodes. The transmitter is allowed to transmit RF signals for information and power transfer simultaneously in the same time and frequency resource block. As mentioned earlier, since the power receiver is more sensitive to the magnitude of RF signal than the information receiver, it is usually placed closer to the transmitter, as shown at the left-hand side of Fig. 2. With respect to the combined case, the design focus of the separate case is on the transmitter, but not on the receiver. On one hand, the transmitter leverages the beamforming to separate the information and power transfer in space, in order to avoid the information leakage to the power receiver. On the other hand, the transmitter needs to allocate the transmit power to two beams, to achieve a tradeoff between information and power transfer. For example, the WIPT tradeoff can be formulated as an optimization problem of maximizing the secrecy rate subject to the minimum harvested power. It is worth pointing out that, in the sense of maximizing the secrecy rate, the zero-forcing beamforming (ZFBF) and the use of maximum transmit power may not be optimal, since ZFBF and maximum transmit power may reduce the secrecy rate by decreasing the capacity of the legitimate channel from the transmitter to the information receiver and increasing information leakage to the eavesdropper, respectively. If we do not consider the security issues and only aim to maximize the information rate, the above tradeoff is reduced to a relatively simple optimization problem.

Similarly, the separated case may also comprise multiple information and power receivers. If a TDMA or OFDMA protocol is employed, the problem can be transformed to the case with one information receiver and multiple power receivers over each time slot or each subcarrier. In this subcase, if each power receiver, as an eavesdropper, overhears the information individually,



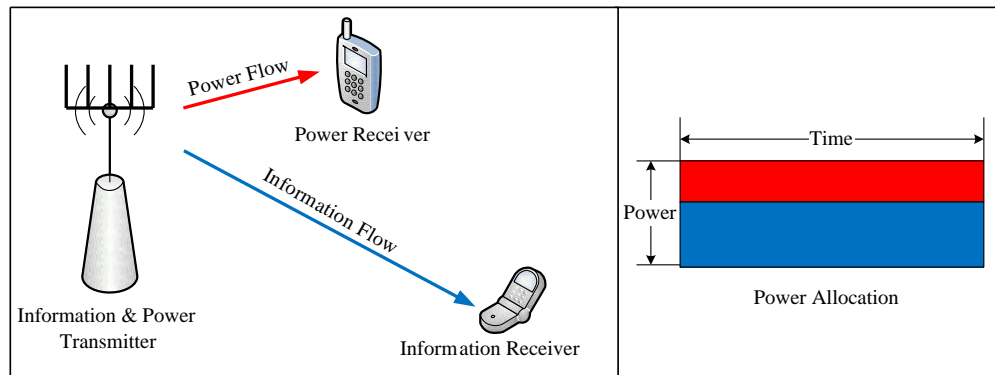


Fig. 2. Model and protocol for separated case of SWIPT.

the secrecy rate is determined by the power receiver with the strongest interception capability. Otherwise, if the power receivers cooperatively intercept the information, the secrecy rate is determined by the combined eavesdropper signal quality. Overall, by maximizing the sum rate in all slots or subcarriers, it is possible to get the optimal receiver scheduling and spatial beamforming schemes. If a SDMA protocol is adopted, all information receivers are active over the same time-frequency resource block. Then, the inter-user interference is inevitable, especially with imperfect CSI at the transmitter. Under such a circumstance, the design of transmit beams is more complicated, and is still an open issue.

### B. Wireless Powered Communication

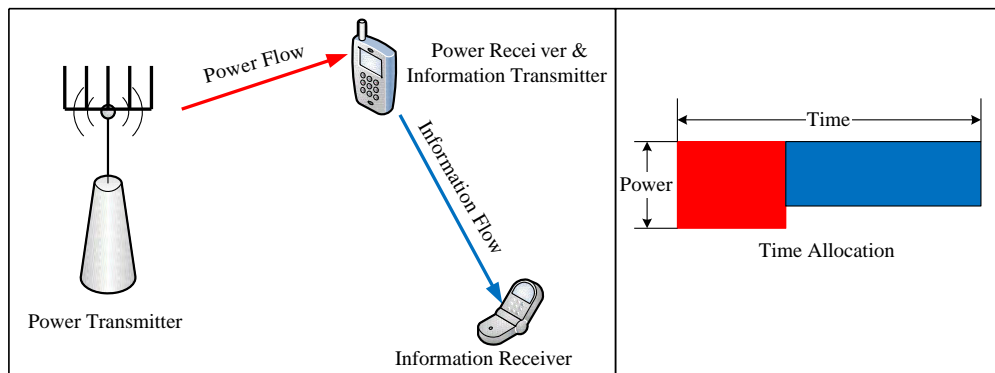


Fig. 3. Models and protocols for WPC.

Different from SWIPT, WPC uses the harvested power to transmit information, and thus

it is also named energy harvesting communications. As a simple example, in medical care applications, the implanted equipment transmits the information it monitors to the instrument outside with the harvested power, as seen at the left-hand side of Fig. 3. With respect to SWIPT, WPC combines information and power transfer more closely, since the harvested power may also affect the information rate.

For the design of WPC, it is important to achieve the optimal tradeoff between information and power transfers. For example, based on the time division protocol, the tradeoff is to determine a switching point between power and information transfers, as shown at the right-hand side of Fig. 3. Since the power for information transmission comes solely from energy harvesting, the tradeoff based on the time division protocol can be formulated as an optimization problem maximizing the information rate with a given transmit power or minimizing the transmit power subject to a minimum rate.

More recently, several new technologies were introduced to further enhance the performance of multi-antenna based WIPT techniques. For example, large-scale MIMO technique can generate high-resolution spatial beams by deploying tens or even hundreds antennas. The benefit of large-scale MIMO technology for WPC lies in two-fold [12]. First, the transfer efficiency and distance can be significantly improved by making use of its large array gain, so as to enable long-distance WPC with low power. Second, the high-resolution beam can reduce the information leakage to an unintended node to achieve information security. As the number of antennas increases, the performance gain becomes larger, which is a main advantage of LS-MIMO technique based WPC.

### *C. Integration of SWIPT and WPC*

In fact, SWIPT and WPC can be integrated to give a more general WIPT scenario described as follows. First, the transmitter sends information and power to one or multiple receivers, and then the power receivers send information to their next-hop receivers using the harvested power. The design of such a general WIPT can be considered as a concatenation of SWIPT and WPC. Its transmission protocol is also based on an integration of SWIPT and WPC components. In other words, each time slot is divided into two durations, one for SWIPT and the other for WPC.

If the time division protocol is adopted at SWIPT stage, each time slot is partitioned into three non-overlapped durations. Typically, the power receiver will allocate constrained time duration to

either receiving information from the power transmitter, or transmitting information to the next-hop receiver, which may lead to a low efficiency. Actually, it is possible to transmit and receive information simultaneously at the power receiver with recently introduced full-duplex technology [14]. For example, if the information transmitter at SWIPT stage is also the information receiver at WPC stage, the current full-duplex technology can be exploited to improve the efficiency. A potential problem of the full-duplex technology is the self interference from the information transmitter to the receiver. Fortunately, multi-antenna technology can be used to cancel the self-interference by making use of the spatial degrees of freedom. Hence, multi-antenna based WIPT technique combining full-duplex can significantly improve the performance.

In all scenarios, multi-antenna based WIPT technique can solve a series of challenging issues, making it an attractive solution to provide efficient, reliable, secure, and long-distance transfer. In Fig. 4, we give a summary of various multi-antenna based WIPT techniques together with their corresponding transfer protocols.

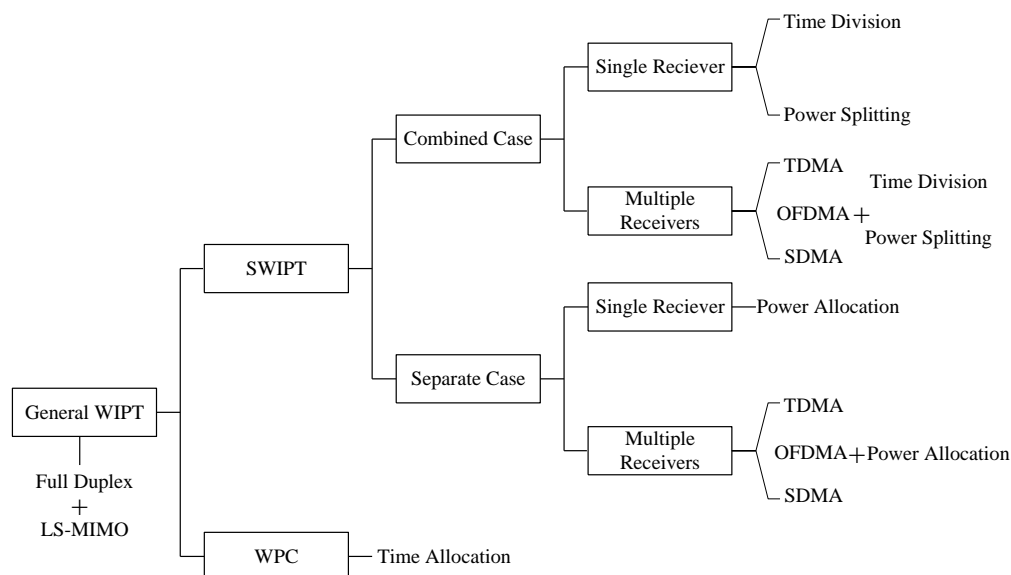


Fig. 4. A summary of multi-antenna based WIPT.

### III. WIRELESS INFORMATION AND POWER TRANSFER TRADEOFF

In this section, we focus on the tradeoff or balance between wireless information and power transfer in single user multi-antenna systems. As discussed earlier, information and power trans-

fers have different performance metrics. For example, information transmission mainly concerns the rate, delay, and security, while power transfer emphasizes the efficiency and distance. Intuitively, the goals for information and power transfers are inconsistent, and even contradictory. Thus, it is of importance to achieve an optimal tradeoff in the design of WIPT.

It is a common practice to achieve the performance objectives by optimizing the system parameters, e.g., transmit beam, transmit power, transfer duration, user scheduling, channel selection, and transfer protocol. For SWIPT, since the performance objectives are relatively independent, the tradeoff is usually formulated as three types of optimization problems. First, a multi-objective optimization scheme can be adopted, in order to maximize the two performance indexes simultaneously. Second, the objective can be expressed as a general utility function. For example, it is reasonable to take a weighted sum of the efficiency as the objective. Third, the problem can be formulated by maximizing one performance index subject to a constraint on the other performance indices. For instance, a common problem in the existing related literatures is to maximize the information rate subject to a minimum harvesting power constraint. Different from SWIPT, WPC relates the two performance metrics more closely, since the harvested power is used for information transmission. Therefore, the tradeoff for WPC has a direct and single formulation. In what follows, through two typical tradeoffs for multi-antenna technique based WPC, we present their protocol designs and parameter optimizations.

#### *A. Information Rate Maximization in Traditional Multi-Antenna Systems*

First, let us consider a traditional multi-antenna based WPC technique, as shown in Fig. 3. A multi-antenna power transmitter charges a power receiver via RF signals at the beginning of each time slot, and then the power receiver sends information to an information receiver. Note that the power transmitter and the information receiver can be the same node in some cases. This is a typical application scenario in medical care (e.g., microchip implant) and underwater monitoring.

In order to improve the power transfer efficiency and thus maximize the information transmission rate, energy beamforming is conducted at the power transmitter. In practice, the multi-antenna power transmitter directs the RF signals to the receiver according to the current channel state, so as to overcome the negative effects of channel fading and propagation loss. Note that the performance of energy beamforming depends on the accuracy of CSI at the transmitter. As

mentioned earlier, the CSI is obtained through feedback in FDD systems or direct estimation in TDD systems. Considering the fact that the power transmitter and the information receiver are in general separate, limited feedback based on a quantization codebook is a more practical choice. In such a system, the harvested power at the information transmitter can be considered as an increasing function of CSI feedback amount, transfer duration, and transmit power, and at the same time a decreasing function of transfer distance.

With the harvested power, the information transmitter sends information to the receiver in the remaining time of the slot. In general, the average transmit power for information transmission is equal to the quotient of the harvest energy and the duration left for information transmission. Therefore, according to Shannon capacity equation, the average amount of information transmitted during a time slot can be expressed as a function of the average transmit power. Finally, the average information transmission rate can be derived through dividing the average amount of information transmitted during a time slot by the length of a time slot. Intuitively, it is a function of transmit power at the power transmitter, power transfer duration, and CSI feedback amount.

Taking the maximization of average information transmission rate as the optimization objective, we can derive the optimal transfer duration for a given CSI feedback amount, namely the switching point for power and information transfers. By adjusting the amount for CSI feedback, we can get different tradeoffs.

So far, we have only given a basic example. In fact, it can be extended to several more complex cases. First, when the information transmission has a certain quality of service (QoS) requirement, the above optimization problem should include a QoS constraint. It is worth pointing out that, given transmit power and feedback amount, there may be no feasible solutions for transfer duration. To solve it, we should increase transmit power or feedback amount. Additionally, if the system is power-limited, we can formulate the problem as minimizing the transmit power, while satisfying the QoS requirement. Second, the basic model can also be naturally extended to the case of a general WIPT. Similarly, we need to add a minimum rate constraint for the information transmission from the power transmitter to the power receiver. Meanwhile, if time division protocol is adopted, an optimization variable of information transfer duration should be added. Otherwise, if power splitting protocol is adopted, the added optimization variable should be the power splitting ratio instead. Third, in the case of an eavesdropper overhearing the information sent from the information transmitter, the above optimization problem is transformed

to maximizing the secrecy rate.

### *B. Energy Efficiency Maximization in LS-MIMO Systems*

LS-MIMO technique can generate a high-resolution spatial beam through the deployment of a large number of antenna elements, and thus achieve substantial transfer efficiency and distance gains. In this case, we consider a WPC system, where both the power transmitter and the information receiver are equipped with a large-scale antenna array.

To fully exploit the benefits of LS-MIMO techniques, the transmitter needs to know the exact CSI. However, due to a large amount of feedback (proportional to the number of antennas) in LS-MIMO systems, the CSI feedback scheme is practically infeasible. Thus, LS-MIMO systems usually work in TDD mode, and therefore the CSI can be estimated by making use of channel reciprocity. However, due to transceiver hardware impairment, the estimated CSI may be imperfect, resulting in certain performance loss. Hence, the CSI accuracy is also a decisive factor in determining the performance. Note that the numbers of antennas at the power transmitter and the information receiver are usually quite large (e.g., more than 100). According to the law of energy conservation, the harvested power at the power receiver (namely the information transmitter) is a function of transmit power at the power transmitter, power transfer duration, and CSI accuracy based on TDD mode. In addition, due to channel hardening in LS-MIMO system, it is also a deterministic function of the number of transmit antennas. Similarly, with the harvested power, the average information transmission rate can be expressed as a function of transmit power, transfer duration, CSI accuracy, the number of power transmit antennas, and the number of information receiver antennas by making use of Shannon capacity expression.

The energy efficiency, defined as the bits transferred per Joule energy, is a key performance metric for WIPT [15]. Therefore, we maximize the energy efficiency to get the optimal tradeoff for such an LS-MIMO based WPC system. As pointed out earlier, the amount of information transferred during a time slot can be computed through multiplying the average information transmission rate by the length of a time slot, and the total energy consumption is the sum of the energy consumption in the power amplifier at the power transmitter and the constant energy consumption in the transmit filter, mixer, frequency synthesizer, and digital-to-analog converter (which are independent of the actual transmit power). Hence, by maximizing the ratio of the amount of information transmission and the total energy consumption, we can derive the optimal

transfer duration. Similarly, we can add QoS and secrecy requirements on the basis of the above problem. Note that if the extended problem has no feasible solutions, we can make it feasible by simply adding more antennas at the power transmitter or the information receiver, which is a main advantage of the LS-MIMO based WIPT techniques.

#### IV. PERFORMANCE ANALYSIS AND SIMULATIONS

In this section, we present some simulation results to validate the tradeoffs of multi-antenna based WPC technique, where the power transmitter and the information receiver are integrated in one node. The parameters used are defined as follows. We set the length of a time slot as  $T = 5$  ms, noise variance  $\sigma^2 = -125$  dBm, energy conversion efficiency from RF signals to electric energy  $\theta = 0.9$ , constant power consumption  $P_0 = 30$  dBm, and path loss for power transfer and information transmission  $\alpha = \beta = 10^{-2}d^{-\nu}$ , where  $d$  is the transfer distance and  $\nu = 4$  is the path loss exponent. Note that, in the given path loss model, a path loss of 20 dB is assumed at a reference distance of 1 meter. In addition, we use  $B$  and  $\rho$  to denote the feedback amount in traditional multi-antenna systems and the CSI accuracy in LS-MIMO systems, respectively.

First, let us consider the tradeoff for a traditional multi-antenna based WPC technique with  $N_t = N_r = 4$  and  $d = 10$  m. As discussed in Section III.A, we take the maximization of average information transmission rate as the optimization objective and adjust the transfer duration. It is shown in Fig. 5 that the feedback amount  $B$  has a great impact on the tradeoff, and thus affects the information rate. In comparison to the case without feedback, a small feedback amount, e.g.,  $B = 2$ , can increase the information rate remarkably. However, as the amount of feedback increases, the additional gain in term of information rate diminishes. As seen from the results, with a finite feedback amount of  $B = 4$ , the performance gap to the ideal case (full feedback) is small. Thus, the insight obtained here is that, with even limited CSI feedback, the traditional multi-antenna technique can effectively enhance the performance of WIPT.

Second, let us examine the effect of LS-MIMO technique on the tradeoff of WPC with  $N_r = 100$ ,  $\rho = 0.9$ , and  $d = 50$  m. This corresponds to a long-distance power transfer scenario. With respect to traditional multi-antenna techniques, only LS-MIMO technique can support such a long transfer distance without consuming more transmit power, which is a very appealing characteristic feature. Take energy efficiency as the optimization metric, we derive the optimal



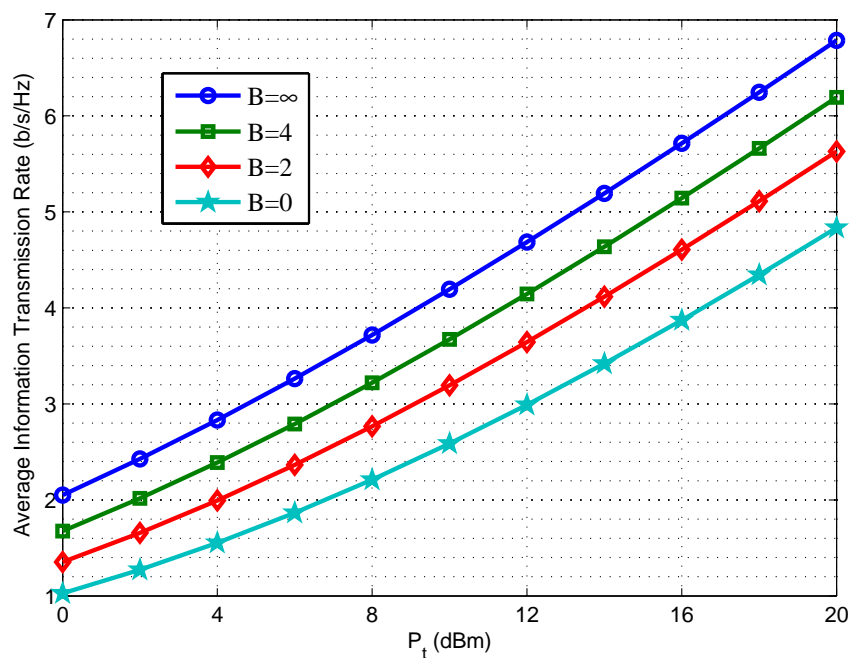


Fig. 5. Information rate of traditional multi-antenna based WPC technique with different feedback amounts.

tradeoff of LS-MIMO technique based WPC, as shown in Fig. 6. It is found that the number of antennas has a great impact on the energy efficiency, which validates an antenna number versus energy efficiency tradeoff. By adding more antennas, the energy efficiency can be improved further, which enables a high QoS for WPC with an affordable power even in the presence of imperfect CSI.

## V. CONCLUSION AND FUTURE WORKS

This article reviewed the key technologies in WIPT and discussed several challenging issues, i.e., transfer efficiency, distance, tradeoff, and security. Through summarizing the existing works on multi-antenna based WIPT techniques, this paper gives a comprehensive tutorial covering both parameter optimization and protocol design, and proposes to use full-duplex and LS-MIMO technologies to solve the challenges in various WIPT scenarios. In particular, a concept of WIPT tradeoff based on multi-antenna technique is introduced and analyzed in detail. Finally, the tradeoffs are validated through simulations using the proposed schemes in two typical multi-antenna scenarios.

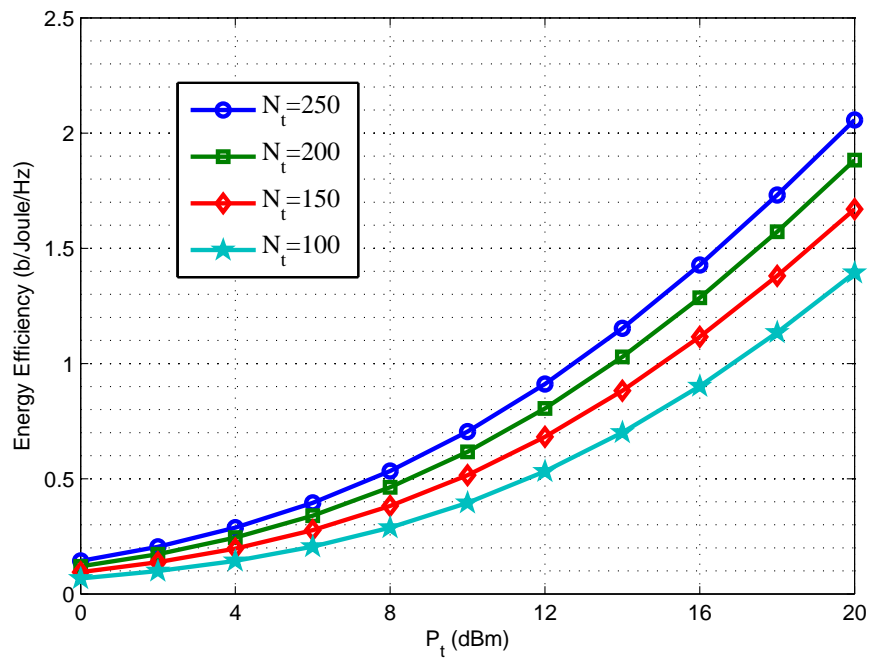


Fig. 6. Energy efficiency of LS-MIMO based WPC technique with different numbers of antennas.

It is worth pointing out that there are still many open issues for WIPT, especially for multiuser WIPT. First, the user scheduling schemes should be carefully designed to balance the QoS requirements, resource constraints, and information security. Second, transmit beams need to be elaborately constructed to achieve a proper tradeoff between information and power transfers, in particular with imperfect CSI. Third, the benefits of advanced multi-antenna techniques for WIPT should be further exploited. For instance, the self-interference of full-duplex techniques is adverse to information transmission, but can be harnessed to enhance power transfer. Hence, it is not optimal to cancel the self-interference completely, and a more in-depth investigation is required.

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