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Wireless Information and Power Transfer: Spectral Efficiency Optimization for Full-duplex System

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Abstract: *In terms of modern applications of wireless sensor networks in smart cities, relay terminals can be employed to simultaneously deliver both information and energy to a designated receiver by harvesting power via radio frequency (RF). In this paper, we propose time switching aware channel (TSAC) protocol and consider a dual-hop full-duplex (FD) relaying system, where the energy constrained relay node is powered by RF signals from the source using decode-and-forward (DF) relaying protocols. In order to evaluate system performance, we provide an analytical expression of the achievable throughput of two different communication modes, including instantaneous transmission and delay-constrained transmission. In addition, the optimal harvested power allocation policies are studied for these transmission modes. Most importantly, we propose a novel energy harvesting (EH) policy based on FD relaying which can substantially boost the system throughput compared to the conventional half-duplex (HD) relaying architecture in other transmission modes. Numerical results illustrate that our proposed protocol outperforms the conventional protocol under the optimal received power for energy harvesting at relay. Our numerical findings verify the correctness of our derivations and also prove the importance of FD transmission mode.*

Keywords: Energy harvestingFull-duplexDecode-and-forwardOutage capacityDelay-constrained

1 Introduction

It is undoubted that wireless communication systems have attracted much research interest in recent years. In particular, energy-aware radio access solutions can be implemented to deal with the massive increase in the consumption of energy in telecommunication networks and the efficient use of power is important for energy optimization. In addition, applications based on internet of things networks have become increasingly popular, so they require novel approaches for energy saving applied in low-power devices. Energy harvesting is the amount of energy available at the transceiver node powered by surrounding energy sources such as solar, wave, vibration, and radio frequency.

Since energy harvesting plays an important role in relaying regardless of power optimization at relays which are assumed to be powered by ideal power sources. In sensor networks and cellular networks, wireless devices using rechargeable or replaceable batteries are often out of order in a short period of time, as the battery powered devices in such wireless networks usually suffer from limited operating times. Unlike portable devices, the maintenance cost of sensor nodes is often higher in case they are replaced or recharged. Additionally, it is noted that it may be dangerous to replace batteries in toxic environments and powering medical sensors implanted inside human bodies is also challenging. To supply a perpetual power in such networks, energy harvesting is considered as a potential method to prolong lifetime of wireless devices [1, 2]. To take advantage of information transfer over wireless channels, receivers can scavenge power from the transmitted signal. Since ambient radio signals can carry energy and information, energy harvesting brings more major advantages compared to the conventional grid power supply [3].

Since radio frequency (RF) signals are capable of carrying both information and energy, a new concept in green wireless communications was put forward, namely simultaneous wireless information and power transfer (SWIPT). To take advantage of SWIPT, more practical receiver architectures have been developed with two separated circuits to carry out energy harvesting and information decoding [4, 5]. There are two major schemes in the receiver, including time switching and power splitting. The authors in [4] presented performance of system under capability of energy harvesting applied in a simple single-input single-output scenario while multiple-input multiple-output (MIMO) broadcasting scenarios was introduced in [6].

In order to obtain practical insights in term of optimal time and power allocation. The work in [7] focused on time allocation policy for the two transmitters in case the efficiency of energy transfer is maximized by an energy beamformer under the impact of Channel State Information (CSI) received in the uplink by the energy transmitter. Furthermore, in [8], the time fraction in TSR impacts on the optimal throughput and such parameter can be found in a numerical method.

We next consider several system models regarding existing cooperative networks with capability of energy harvesting. Firstly, the employed relay in SWIPT networks [9, 10] or the source terminal [11] can harvest energy from the radiated signal of the source terminal or the employed relay. Secondly, in multi-hop networks, energy is transferred to remote terminals via multi-hop [12, 13]. In multi-hop systems, the high path loss of the energy-bearing signal can be eliminated [12]. Unlike [12], the authors in [13] investigated a multi-antenna relay adopting two separate terminals with capability of information processing and power transfer, respectively, and the expressions of the transmission rate and outage probability were presented under the impact of remote energy transfer. In addition, relay selection is considered as solution to determine a tradeoff between the efficiency for the information transmission and the amount of energy forwarded to the energy receivers [14, 15, 16].

Furthermore, full-duplex (FD) mode was evaluated, in which it allows transmitting and receiving signals at the same frequency band at the same time slot. Various theoretical analysis and practical designs have been conducted in terms of FD networks like in [17, 18, 19, 20, 21]. Thanks to the use of FD mode, the resources are utilized more efficiently and it can double the spectral efficiency compared to half-duplex (HD) mode. However, due to practical constraints, the performance of FD communication can be affected by the self-interference (SI) stemming from FD node transmission.

In addition, energy harvesting along with throughput optimization has been mentioned in previous works. In [22] and [23], throughput optimization with constraints was studied under a static channel condition for obtaining best efficiency of energy harvesting transmitters.

Moreover, energy harvesting based on power control policies for wireless powered transmission over fading channels suffer from several problems, i.e., the randomness of RF energy source, wireless fading channels and the maximum power constraints. To address this situation, several existing works have considered offline optimal power control designs for fading channels [24, 25]. The work in [25] considered that the offline optimization in an efficient optimal solution was presented to achieve optimal energy efficiency. Although the authors in [26] investigated the offline scheduling and formulated the corresponding performance optimization problems of two-way relay networks, the statistics of energy and fading channels are assumed to be parameters at the transmitter, and optimal function can be derived in a numerical manner under high computation.

The authors in [27] considered that the optimal time splitting coefficients for the full-duplex dual-hop relaying lead to enhance the system throughput in comparison with the traditional half-duplex relaying scheme for all kinds of modes including instantaneous transmission, delay-constrained transmission, and delay-tolerant transmission. The energy-constrained FD relay node can be applied in the multiple-input single-output (MISO) system; the optimal power allocation and beamforming design are investigated in [28]. In another line of research, the FD decode-and-forward system using the time-switching protocol is embedded in the multiple antenna-assisted relay to obtain more energy from the source and transfer signal to the destination as in [29, 30]. Interestingly, in order to achieve the maximal throughput performance, the optimal time switching coefficient is adaptively selected based on channel state information (CSI), accumulated energy, and threshold signal-to-noise ratio (SNR) [31, 32] and [33].

Motivated from the previous works [27], we focus on optimal throughput of a two-hop case, where RF energy harvesting powers the relay. In this paper, the impact of FD transmission is investigated in terms of the system throughput to determine the performance of RF energy harvesting relaying system. The two-antenna configuration is proposed in the FD mode, where the relay is equipped with two antennas, one for transmitting signal and the other one for receiving signal simultaneously. In this paper, two different transmission modes are investigated, namely instantaneous transmission and delay-constrained transmission. Furthermore, we examine the throughput of DF relaying protocols and characterize the fundamental trade-off between energy harvesting and system throughput. In order to compare with the effect of the FD relaying architecture, the HD relaying architecture is also investigated. The main aim of this paper is that FD relaying is an attractive and promising solution to enhance the throughput of RF energy harvesting-based relaying systems.

Comparing to [27] and [28], although this work consider a same system model with those works, our investigation also design a novel wireless power transfer strategy to improve the system performance. The authors in [27] consider a conventional time splitting protocol, in which relay switches from energy harvesting to information transfer with fixed EH fraction time allocated. While [28] design a self-energy recycling strategy for energy harvesting at relay, this EH manner can collect transmitted signal itself and scavenge to energy. Contrarily, our work redesigns the conventional time switching protocol as in [27] to a novel EH schedule. The proposed EH will acquire the channel state information (CSI) to allocate amount of EH time. In particular, the relay transmission power can be preset level. The magnitude of self interference at relay thus can be controlled based on relay transmitted power, which can improve the system performance.

The main contributions of our paper are summarized as follows: A new protocol for wireless power transfer called time switching aware channel protocol (TSAC) is proposed in FD DF relaying networks and further analysis is presented as well. We provide analytical expressions in instantaneous transmission mode for both cases, i.e., one antenna and dual antennas at relay node in EH-based networks. The outage probability and average throughput for delay-constrained transmission mode are derived in closed-form expressions for tractable computation. The optimal values can be achieved in various simulation results. The advantages of the proposed protocol are also compared with the previous works. The most critical performance metric (i.e., optimal throughput efficiency) is thoroughly analyzed and

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systematically validated via comparative simulations.

2 System model and energy harvesting protocol

2.1 System model

As shown in Fig. 1 a, we consider a two-hop relaying network consisting of one source denoted by SS, one destination denoted by DD, and one intermediate node denoted as RR. It is assumed that the source and destination node are equipped with single antenna, i.e., SS and DD are provided with single antenna, while RR is equipped with two antennas, and operated in FD mode. In addition, the relay node is assumed to have no extra embedded energy sources so it requires to harvest energy from the received RF signal from the source node [2, 5, 8, 14, 20, 27, 28, 29, 32]. The TSAC protocol is shown in Fig. 1 b, in which the relay adjusts EH time to meet the installed transmit power every block time. Therefore, at time slot ith, the relay node will energy harvesting with $\alpha_i T$ seconds.

Figure 2 shows basic block diagram for the SWIPT system, where TSAC is deployed. The system has one switching unit and one combining unit compared to conventional systems as Fig. 2 a or as system models introduced in [5, 27]. As illustrated in Fig. 2 b, we design an architecture exploiting dual antennas to harvest energy at relay during the energy harvesting phase as [27]. In this scheme, we consider WPT phase in which the switching units change the role of both transmitting and receiving antenna to receive energy via RF signal as [27, 30]. Then, those RF signals are combined and used to feed the energy harvester. It is worth noting that case 2 is a natural choice, since it fully exploits the available hardware resources (i.e., antenna components in multiple-input multiple-output (MIMO) systems) to collect more energy [30]. Nevertheless, due to its straightforward implementation, case 1 could be more practical in certain applications.

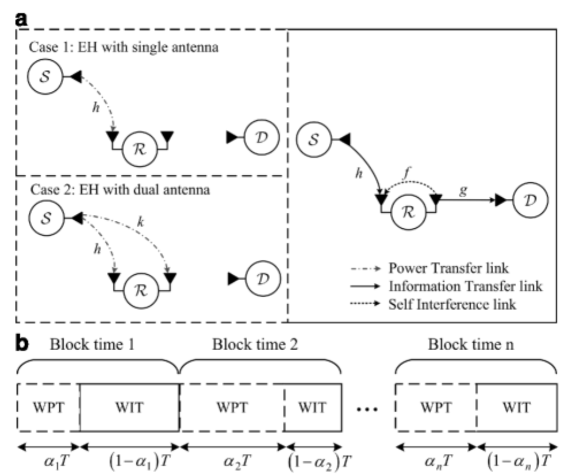

Fig. 1 :Two-hop relaying networks in full-duplex communication with SWIPT. **a** Describing two phases of cooperative relay energy harvesting communications with two scenarios of energy harvesting at relay node. **b** TSAC protocol for energy harvesting full-duplex relaying network

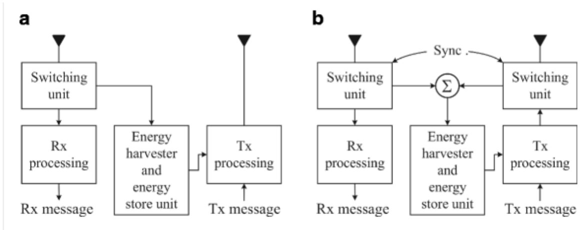

Fig. 2 Receiver architecture of relay with energy harvesting. **a** Relay node with single antenna EH. **b** Relay node with dual antennas EH

2.2 Channel model

We assume that the S→RS→R and R→DR→D channel links include both large-scale path loss and statistically independent small-scale Rayleigh fading. We denote d_1 is distance between source and relay node and d_2 is distance between relay and destination node. We also denote the main channels such as *h* and *k* are the links from the source to first antenna and second antenna at relay, respectively, and *g* is the channel from relay to destination node. It is also assumed that the main channels experience Rayleigh fading and remain constant over the block time *T* and varies independently and identically from one block to the other.

In this paper, we also use character *f* to represent the SI link at relay node as normal manner. Due to the short distance of this link, the line-of-sight (LoS) path is likely to represent to SI channel; hence, it can be shown that the Rician distribution can handle such SI channel as [18]. However, due to the complicated Rician fading probability density function (PDF), the analytical expressions become extremely difficult. Fortunately, the alternative model of the Nakagami-*m* fading distribution provides a very good approximation to the Rician distribution. Motivated by this, and to simplify in the analysis, we adopt the Nakagami-*m* fading with fading severity factor m_f and mean λ_f to model the loop interference channel in this paper.

So that $|h|^2$ and $|k|^2$ are independent and identically distributed (i.i.d.), exponential random variables with mean λ_h and λ_k, where $\lambda_h = \lambda_k$, $|g|^2$ is exponentially distributed with mean λ_g. The self-interference power link at relay, i.e., $|f|^2$, is a Gamma random variable distributed as $\Gamma(m_f, \lambda_f / m_f)$, in this paper we also assume m_f is an integer number.

The transmit power of source and relay are represented by PSPS and PRPR, respectively. Due to the shadowing effect, the direct transmission between source node and destination node does not exist [2, 5, 8, 20, 27, 29, 32]. The FD mode causes self-interference, which can be addressed by the novel methods in the literature as [17, 19] and these algorithms are beyond the scope of our paper. Unfortunately, the residual self-interference still exists after interference suppression in the practical receiver architecture and it also impairs the performance of FD relay networks as [17, 18, 19, 20, 21, 27]. In this

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paper, we mainly focus on the impact of the residual self-interference on system performance in terms of the harvested power.

2.3 TSAC protocol description

In this subsection, the energy harvesting protocol is presented. In spirit of [31, 32, 33] suggesting adaptive time switching strategies for SWIPT system, we redesigned TS protocol related to CSI for FD relay transmission mode, named TSAC protocol. The detail of modified TSAC protocol is described as below. The harvested energy is stored in a rechargeable battery and then totally used to feed power circuits and transmit information to the destination node. Particularly in TSAC policy, each communication block time is slit into two slots, including wireless power transfer (WPT) slot and wireless information transfer (WIT) slot as mentioned in [4, 5, 6, 7, 11, 12, 27, 31, 32, 33]. In each block time, WPT slot represents the first $\alpha_i T$ of block time while the WIT slot stands for the rest of $(1-\alpha_i)T$ of block time. During WIT phase, the source transmits its symbol toward the intermediate relay simultaneously, the cooperative relay retransmits its decoded symbol to destination at the same time and bandwidth. The relay thus suffers from loop interference (LI).

Before further description, some important symbols are listed and defined in Table 1. Moreover, regarding the proposed WPT policy, RR will operate with the preset transmit power, PRPR, and thus RR node needs to exactly determine the time duration for WPT to harvest a sufficient amount of preset energy, Ei=PR(1−αi)TEi=PR(1−αi)T.

This process can be done as steps below. Because relay only harvests sufficient amount of energy, EEHi=f(αi)EiEH=f(αi)(where $f(\alpha_i)$ means that function of α_i), one can exactly determine the EH time by equaling amount of harvested energy and that of preset energy, i.e., EEHi=EiEiEH=Ei. Finally, the EH time duration, α_i, is derived. It is noted that the suggested TSAC protocol does not require more additional time slot since the total frame for communication is the same as [27] (see Remark 1), and the preset relay transmit power is a constant value (PRPR) while the EH time is a function of the random variable WPT channel gain(s) as [31, 32, 33].

As aforementioned, to exactly determine this duration of energy harvesting time, channel gain(s) of WPT link is an important parameter(s). Therefore, we assume that the channel state information (CSI) during the first hop is available at source and relay node, which can be obtained by using novel estimation algorithm. Interestingly, the TSAC protocol adjusts the WPT time duration, α_i, in each time slot to satisfy amount of installed power PRPR. In contrast, the fixed-time allocation protocol in [5, 27], the harvested power, PRPR, vary in each block based on channel gain.

3 Numerical results

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In this section, numerical simulation results are demonstrated to validate analytical expressions as concerns in the previous section, and the impact of key system parameters is investigated in detail in terms of system throughput. The energy harvesting efficiency is set η=0.8, while the path loss exponent is set m=3. The distances, d_1 and d_2 are normalized values which are set d_1=3 and d_2=1, respectively. The simulation environments are associated with the detailed parameters as γ0=10 dB,λf=0.01,λh=1,λk=1,λg=1,PS=26 dBγ0=10 dB,λf=0.01,λh=1,λk=1,λg=1,PS=26 dB and noise terms as σ2D=−5 dB,σ2R=−10 dBσD2=−5 dB,σR2=−10 dB. In this subsection, we present simulation results to verify the analytical results. The throughput performance is calculated by averaging the throughput values over a 100,000 blocks, while fading channels for each block is perfectly independent.

Figure 3 illustrates the impact of received power at relay node on the instantaneous throughput. To compare the performance of FD and HD relay, we set $|f|^2$=0.05,$|h|^2$=1.2,$|g|^2$=1.4,$|k|^2$=1. The figure proves that the analytical results based on curves match well with the simulation results. It is noted that the optimal received power at relay for single antenna in HD case and FD case is smaller than those schemes with dual antennas, and the highest instantaneous throughput of FD case outperforms the HD case. When the received power is small, more energy can be collected to facilitate the information transmission while more received power or strong loop-back interference is produced such as the excessive amount of harvested energy, which is the primary cause of worse system performance.

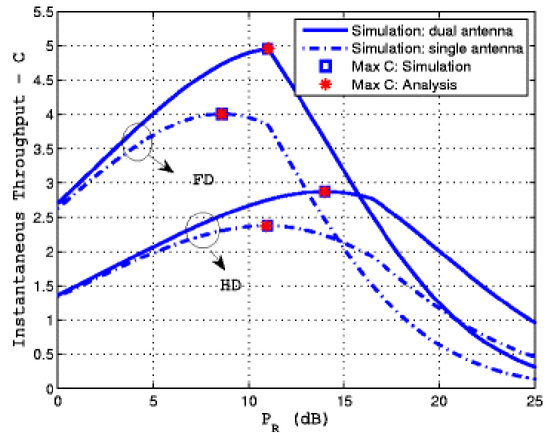

Fig. 3 Instantaneous throughput versus the received power at the relay

The average throughput in delay constraint mode is presented in Fig. 4. It can be observed that the dual antenna case outperforms the single antenna case in terms of the received power at relay. In fact, the dual antennas case can harvest more energy with less transmit power. However, when the transmit power is larger than the optimal harvested power, it results in lower average throughput caused by loop-back interference. On the other hand, the gap between throughput of single antenna and dual antennas is still trivial due to short time for energy harvesting. In general, there should be a balance between energy harvesting capability and noise processing. One can increase PRPR to the optimal value, at approximately 10 dB to achieve optimal

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throughput. As the previous illustration, it is confirmed that FD relay is better than HD relay when the received power at relay is small.

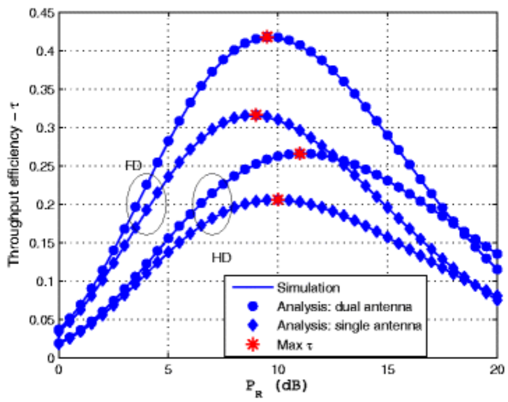

Fig. 4Throughput efficiency versus PRPR in FD relay with m_f=1

Next, it can be observed that throughput performance improves as increasing transmit power of the source node as in Fig. 5. To evaluate the impacts of the factor $m_f$in Nakagami channel of SI on system performance, in this experience we set λ_f=0.1 and PR=PS−10PR=PS−10 (dB). The smallest of $m_f$brings the highest throughput performance. A general observation is that the dual antenna model significantly outperforms the single antenna counterpart at any values of transmit power of the source. Interestingly, when the transmit power overcome about 40 dB, the throughput still remain the peak value in stable floor.

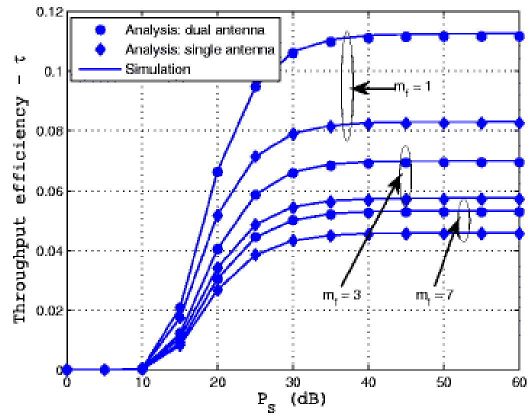

Fig. 5 Throughput efficiency versus PSPS with difference case of m_f, λ_f=0.1 and PR=PS−10PR=PS−10 (dB)

To illustrate the impact of noise variance at relay and destination node in case of optimal throughput, Figs. 6 and 7also show that dual antennas in FD mode outperform FD single antenna. This can be explained as follows: A lower noise variance decreases the outage probability and and hence we obtain more throughput. Conversely, as for higher noise variance, the outage probability increases while the throughput falls dramatically. Thus, the system performance is affected more by erroneous information processing, leading to a waste of resources during the whole block time. In addition, it can be seen that the impact of noise term at relay affects the noise term at destination more. As a result, throughput performance in Fig. 7 declines sharply when noise varies from − 5 to 5 dB.

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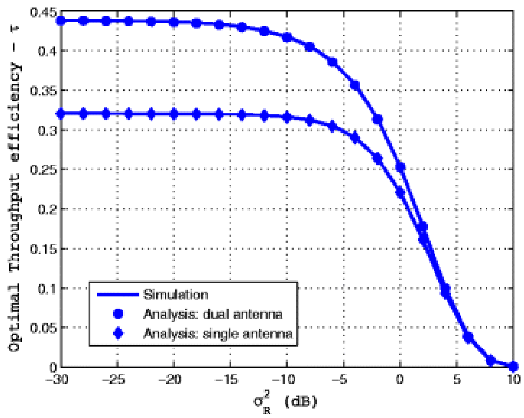

Fig. 6 Throughput efficiency versus σ2DσD2 with m_f=1

In Fig. 8, the simulation results present the throughput efficiency versus γ_0 and compare with existing protocols in [27] and [28]. The main observation is the effect of threshold SNR on throughput in delay constraint mode using TSAC, which is investigated with different quantities of antennas, especially in comparison with traditional energy harvesting protocols. The simulation parameters are installed as α=0.2,PR=10 dBα=0.2,PR=10 dB. The throughput in case of TSAC is better than the traditional case due to optimal time for energy harvesting which is solved in the proposed TSAC. In case of γ_0 described below 14 dB, the proposed protocol related to the optimal throughput efficiency outperforms the existing protocols. However, in high threshold regime, the self-energy recycling protocol proposed in [28] is slightly better than those schemes. In general, this figure reveals that the FD relay has worse performance at higher threshold SNR, which means the system may require higher bit per channel.

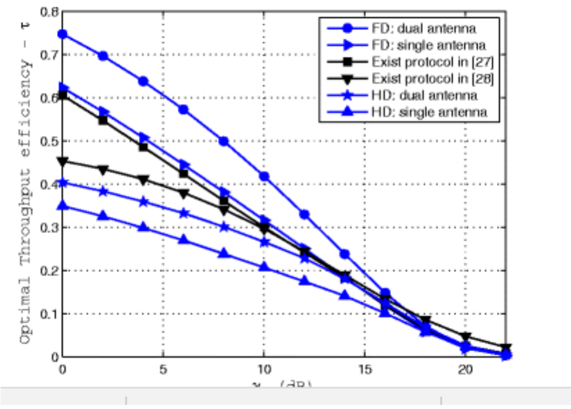

Fig. 8 Throughput efficiency versus γ_0 and the comparison with existing protocols in [27, 28] with λ_f=−20dB and m_f=1

As depicted in Fig. 9, the dual antenna FD relay based on TSAC outperforms the single antenna in terms of residual self-interference. When the residual self-interference is greater than −5 dB, throughput decreases significantly, since this loop-back noise impairs the overall performance. Therefore, the self-interference should be remained lower than acceptable value to satisfy system performance and the FD transmission is only beneficial, if the loop-back noise is eliminated. When SI factor ranges from −20 to −5 dB, the performance of TSAC scheme is superior to the existing protocols, but when SI parameters are greater than −5 dB, the optimal throughput of the proposed protocol in [28] is a prime candidate. Thanks to the EH protocol proposed in [28], the loop interference at relay is reused for self-energy recycling. As a result, part of the energy (loop energy) is used for information transmission by the relay and it improves the scheme’s performance.

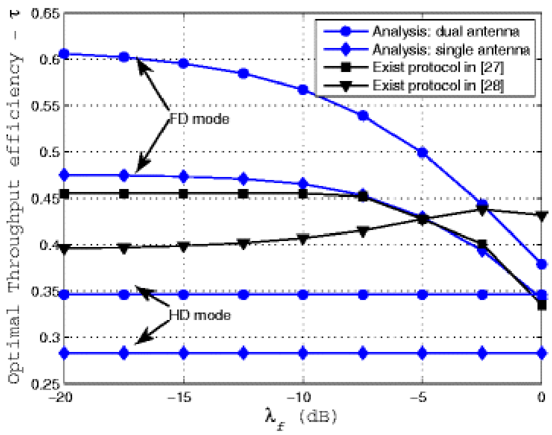

Fig. 9 The impact of residual self-interference on the throughput and in comparison with existing protocols in [27, 28] with γ_0=5 dB and m_f=1

4 Conclusion

In this paper, the throughput of FD and HD relaying in RF energy harvesting systems is investigated. Interestingly, the number of antennas equipped at each relay has significant influence to throughput performance due to the harvested energy at the relay node. Regarding optimal throughput, analytical expressions for the outage probability and throughput capacity of the system were derived. Therefore, the optimal time switching of energy harvesting was comprehensively evaluated. It is confirmed that by employing dual antennas at relay for energy harvesting is beneficial, and the throughput gain is significant when transmit power at source and the received power at relay are carefully calculated. In addition, in comparison with HD relaying networks, our results indicate that FD relaying can substantially boost the system throughput with optimal power allocation policy at energy harvesting-enabled relay. Via mathematical and numerical analysis, the optimal throughput in both instantaneous transmission mode and delay constraint transmission mode can be obtained. More importantly, in order to compute optimal time switching fractions in energy h

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