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Power Control for Full-Duplex Relay-Enhanced Cellular Networks With QoS Guarantees

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ABSTRACT Full-duplex (FD) has emerged as a new communication paradigm with the potential advantage of enhancing the capacity of the wireless communication systems. In this paper, we consider an FD relay-enhanced cellular network, wherein the residual self-interference, the uplink–downlink interference, as well as the relay-access-link interference are the vital restrictions to network performance. To this end, we investigate power control design for the FD relay-enhanced cellular networks, so as to maximize the system spectral efficiency while fulfilling the quality of service (QoS) requirements of both the uplink and downlink user equipments (UEs). We characterize the properties of the optimal transmit power allocation, and propose a power control algorithm based on signomial programming to coordinate the transmit power of the uplink UE, base station, and relay stations to mitigate the interference. Meanwhile, we also derive the closed-form optimal transmit power allocation for the conventional half-duplex (HD) transmission mode. Moreover, we conduct extensive simulation experiments to study the network-level gain of the FD mode over the HD mode in the relay-enhanced cellular networks. Simulation results demonstrate that FD relaying outperforms HD relaying on improving the spectral and energy efficiency, as well as provisioning QoS guarantees for both the uplink and downlink users.

INDEX TERMS Wireless networks, full duplex, relaying, power control, spectral efficiency.

I. INTRODUCTION

Wireless full-duplex (FD) communication allows a node to transmit and receive simultaneously on the same frequency band, such that the link capacity can be doubled compared to the conventional half-duplex (HD) communication. Meanwhile, wireless relaying has evolved from the early theoretic analyses to a practical stage in cellular networks. Deploying relay stations (RSs) in cellular networks can achieve significant performance improvement, including cell capacity enhancement, cell coverage extension, and transmit power saving. Therefore, the combined application of the two technologies in cellular networks should be a promising way to achieve high spectral efficiency. In the new FD relay-enhanced cellular network architecture, the base station (BS) and infrastructure RSs work in FD mode, while the user equipments (UEs) still work in HD mode with the consideration of their capabilities in practical systems. To improve the quality of users' experience, the UEs with good channel conditions, e.g., the cell-center users, can be served by the BS directly, while the ones with unfavorable channel conditions, e.g., the cell-edge users, can be served via the assistance of RSs. It's worthwhile to point out that there exists three types of interference in the FD relay-enhanced cellular networks, which are the vital restrictions to network performance.

First of all, wireless FD communication brings in the ***self-interference*** between the simultaneous transmission and reception paths at each FD node, henceforth self-interference cancellation is a key challenge in realizing the FD nodes. In addition, another key challenge for the FD cellular networks is the ***uplink-downlink interference*** [1] between the concurrent uplink and downlink transmissions taking place within a single cell or multiple neighboring cells. Taking a single cell with a FD BS and several HD UEs for instance, the FD BS can communicate with an uplink UE and a downlink UE simultaneously on each frequency band. In this case, the uplink UE interferes with the reception of the downlink UE, potentially nullifying the benefits from FD communication. The uplink-downlink interference becomes more severe in multicell networks or when the UEs also work in FD mode. Furthermore, when wireless FD relaying is applied, there also exists the ***relay-access-link interference*** between the concurrent relay-link and access-link transmissions due to the simultaneous transmission and reception at the FD RS, which directly affects the achievable end-to-end data rate of the two-hop relaying communication. More importantly, with both the BS and RSs working in FD mode, the relay-access-link interference and the uplink-downlink interference interweave with each other, thus resulting in an extremely complicated interference environment for the FD relay-enhanced cellular networks.

Apparently, the overall performance of the FD relay-enhanced cellular networks could be degraded significantly if the aforementioned three types of interference are not managed properly. The self-interference at each FD node may be easily addressed since the interference information is locally available at the node. So far, substantial works have focused on addressing the self-interference through both analog [2] [3] and digital [4] cancellation schemes. On the contrary, mitigating the uplink-downlink interference and the relay-access-link interference is much more challenging, as it involves the coordination among distributed nodes who couldn't share data information without damaging their information security or sacrificing bandwidth resource. Therefore, efficient interference mitigation scheme especially addressing the uplink-downlink interference and the relay-access-link interference in network scale plays an essential role in reaping the potential benefits of wireless FD communications and wireless relaying in practical systems.

In the literature, with the development of the self-interference cancellation technology, research focus has shifted to addressing the issues related to the wireless FD systems. The authors in [5] and [6] investigated the throughput of the wireless networks with FD radios using stochastic geometry. The authors in [7] studied the network-level capacity gain of FD communication over HD communication. The authors in [8] designed a FD capable media access control (MAC) protocol based on the IEEE 802.11 MAC protocol. The authors in [9] proposed to use spatial interference alignment to address the uplink-downlink interference and characterized the scaling of FD's multiplexing gain in multi-cell FD networks. The authors in [10] devised a queue-length based carrier sense multiple access (CSMA)-type scheduling algorithm for the wireless networks with FD cut-through transmission.

Meanwhile, wireless FD relaying has also attracted considerable research attentions in both academia and industry. The authors in [11] investigated the end-to-end capacity of the two-hop FD relaying channels with decode-and-forward and amplify-and-forward relay, respectively. The authors in [12] studied the outage probability of the end-to-end communication link in the multihop FD relaying systems with decode-and-forward relays. The authors in [13] investigated the outage probability and ergodic capacity of the FD two-way amplify-and-forward relaying channels. Then the authors in [14] developed an opportunistic mode selection scheme for the two-hop relaying systems, wherein the relay switches opportunistically between FD and HD modes so as to optimize the spectral efficiency. The authors in [15] studied the optimal and suboptimal relay selection schemes for the two-hop FD amplify-and-forward relaying systems. The authors in [16] proposed a hybrid relay selection strategy for the two-hop FD decode-and-forward relaying systems to minimize the total power consumption, where the selected relay can work in FD or HD mode according to the channel conditions. The authors in [17] proposed a joint relay and antenna selection scheme for the two-hop FD amplify-and-forward relaying systems, so as to maximize the end-to-end signal-to-interference and noise ratio. The authors in [18] proposed the best-worst-channel relay selection scheme for the FD two-way amplify-and-forward relaying systems. The authors in [19] derived the upper and lower bounds on the end-to-end achievable rate of the FD MIMO decode-and-forward relaying systems with the assumption that the self-interference can be cancelled completely. Note that these existing works mostly concentrate on the theoretical analysis of system performance, mode selection, and relay selection in the FD systems, as well as power control in the two-hop FD relaying links. However, network-level interference mitigation for the FD relaying networks has been rarely discussed.

Motivated by the preceding works, we focus on QoS-aware interference mitigation for the FD relay-enhanced cellular networks. In particular, we investigate power control design for the system spectral efficiency maximization problem with QoS guarantees in the FD relay-enhanced cellular networks. Then main contributions of this paper are as follows.

- We consider a FD relay-enhanced cellular network, wherein both the BS and infrastructure RSs enable simultaneous transmission and reception on the same frequency band. In this scenario, the interference environment is exceptionally complicated. The residual self-interference, the uplink-downlink interference, and the relay-access-link interference are the vital essential restrictions to the network performance.
- We jointly optimize the transmit power of the uplink UE, BS, and RSs, so as to maximize the system spectral efficiency while fulfilling the QoS requirements of the uplink and downlink UEs. We characterize the properties of the optimal transmit power allocation, and propose a signomial programming (SP) based power control algorithm to obtain the globally or at least locally optimal power allocation. For comparison, we also derive the closed-form optimal transmit power allocation for the conventional HD transmission mode.
- We conduct extensive simulation experiments to study the effects of different factors on system performance, and demonstrate the network-level gain of FD relaying over HD relaying.

The rest of this paper is organized as follows. In Section II, we present the system model and formulate the power control optimization problem. In Section III, we elaborate the optimal QoS-aware power control desgin for the FD relay-enhanced cellular networks. In Section IV, we present the optimal power control scheme in the HD transmission mode. In Section V, we present simulation results and performance analyses. In Section VI, we conclude the paper.

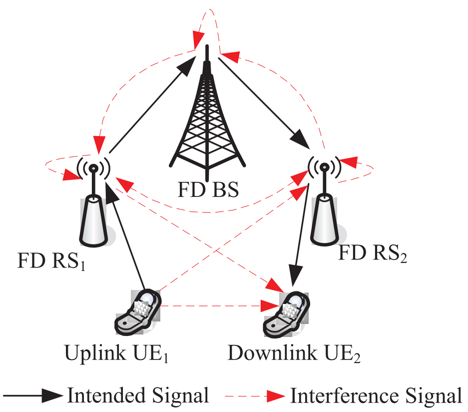

FIGURE 1. Full-duplex relay-enhanced cellular network.

II. SYSTEM MODEL AND PROBLEM FORMULATION

Consider a FD relay-enhanced cellular network consisting of a FD BS, two FD RSs and two HD UEs, as shown in Fig.1. We concentrate on the coverage extension scenario in which the direct source-destination link is weak and the relay is deployed to help forwarding signal without having own data to transmit. In specific, the uplink UE_1 transmits signal to the RS_1, and simultaneously the RS_1 forwards the decoded received signal to the BS. Meanwhile, the BS serves the downlink UE_2 via another FD RS, i.e., the RS_2. Without loss of generality, a single channel is considered in our work, since the case of multiple channels can be studied in a similar manner. In this case, the uplink and downlink transmissions take place on the same channel at the same time. Consequently, there are three types of interference in the system, i.e., the residual self-interference at the FD nodes, the uplink-downlink interference among the concurrent uplink and downlink transmissions, as well as the relay-access-link interference between the concurrent relay-link and access-link transmissions, as shown by the dashed arrows in Fig.1.

Let $h_{i,j}$ represent the channel gain of the link between nodes i and j, and g_i^{SI} represent the residual self-interference channel gain in the FD node i due to imperfect cancellation. The wireless channels are modelled to be frequency-flat and quasi-static. And with the reciprocity of wireless links, we assume that $h_{i,j} \equiv h_{j,i}$. Let P_i denote the transmit power of node i, and σ^2 denote the average power of additive white Gaussian noise (AWGN) of each link. Accordingly, the instantaneous signal-to-interference-plus-noise ratios (SINRs) of the access and the relay links in the uplink transmission can be respectively expressed as

$$\eta^{\mathrm{UL}}_{\mathrm{UE}_1\to\mathrm{RS}_1} = \frac{H_{R_1,U_1}P_{U_1}}{1+G_{R_1}P_{R_1}+H_{R_1,B}P_B+H_{R_1,R_2}P_{R_2}} \quad (1)$$

$$\eta^{\mathrm{UL}}_{\mathrm{RS}_1\to\mathrm{BS}} = \frac{H_{B,R_1}P_{R_1}}{1+G_BP_B+H_{B,R_2}P_{R_2}} \quad (2)$$

where $H_{i,j} \triangleq |h_{i,j}|^2/\sigma^2$ and $G_i \triangleq |g_i^{SI}|^2/\sigma^2$ are the normalized channel gains, representing channel signal-to-noise ratios (SNRs). In (1), the term $G_{R_1}P_{R_1}$ represents the residual self-interference at the RS_1, while the terms $H_{R_1,B}P_B$ and $H_{R_1,R_2}P_{R_2}$ represent the interference from the BS and RS_2 respectively. Similarly, according to (2), the reception at the BS is interfered by the residual self-interference and the simultaneous transmission at the RS_2.

In the downlink transmission, the instantaneous SINRs of the access and relay links can be respectively expressed as

$$\eta^{\mathrm{DL}}_{\mathrm{BS}\to\mathrm{RS}_2} = \frac{H_{B,R_2}P_B}{1+G_{R_2}P_{R_2}+H_{R_2,U_1}P_{U_1}+H_{R_2,R_1}P_{R_1}} \quad (3)$$

$$\eta^{\mathrm{DL}}_{\mathrm{RS}_2\to\mathrm{UE}_2} = \frac{H_{U_2,R_2}P_{R_2}}{1+H_{U_2,U_1}P_{U_1}+H_{U_2,R_1}P_{R_1}} \quad (4)$$

According to (3) and (4), the reception at the downlink UE_2 is interfered by the simultaneous transmissions at the uplink UE_1 and RS_1, while the reception at the RS_2 is also interfered by the residual self-interference in addition to the simultaneous transmissions at the uplink UE_1 and RS_1.

With the decode-and-forward relaying, the achievable end-to-end spectral efficiencies (bps/Hz) of the uplink and downlink UEs are respectively given by

$$C^{\mathrm{UL}}_{\mathrm{UE}_1} = \log\left(1+\min\left(\eta^{\mathrm{UL}}_{\mathrm{UE}_1\to\mathrm{RS}_1}, \eta^{\mathrm{UL}}_{\mathrm{RS}_1\to\mathrm{BS}}\right)\right) \quad (5)$$

$$C^{\mathrm{DL}}_{\mathrm{UE}_2} = \log\left(1+\min\left(\eta^{\mathrm{DL}}_{\mathrm{BS}\to\mathrm{RS}_2}, \eta^{\mathrm{DL}}_{\mathrm{RS}_2\to\mathrm{UE}_2}\right)\right) \quad (6)$$

Clearly, the overall performance of the considered FD relay-enhanced cellular network largely depends on the management of the residual self-interference, the uplink-downlink interference, and the relay-access-link interference. To this end, the problem of interest in this work is to jointly optimize the power control for the uplink and downlink transmissions, i.e., to optimize the transmit power of the uplink UE_1, RS_1, BS, and RS_2, with the objective of maximizing the overall spectral efficiency subject to the QoS requirements of the UEs as well as the individual power constraints of the transmitting nodes. Mathematically, the optimization problem is formulated as follows:

$$\begin{aligned}\mathrm{P1:}\ &\max_{\mathbf{P}}\ C^{\mathrm{UL}}_{\mathrm{UE}_1}+C^{\mathrm{DL}}_{\mathrm{UE}_2}\\ &\text{s.t. C1:} C^{\mathrm{UL}}_{\mathrm{UE}_1} \geq R^{\mathrm{req}}_{\mathrm{UE}_1}\\ &\quad\ \ \text{C2: } C^{\mathrm{DL}}_{\mathrm{UE}_2} \geq R^{\mathrm{req}}_{\mathrm{UE}_2}\\ &\quad\ \ \text{C3: } 0 \leq P_i \leq P_i^{\max}, \quad \forall i \in \{U_1, R_1, B, R_2\}\end{aligned} \quad (7)$$

where $\mathbf{P} \triangleq (P_{U_1}, P_{R_1}, P_B, P_{R_2})$ is the optimized variable; $C^{\mathrm{UL}}_{\mathrm{UE}_1}$ and $C^{\mathrm{DL}}_{\mathrm{UE}_2}$ are given by (5) and (6), respectively;

$R_{\mathrm{UE}_1}^{\mathrm{req}}$ and $R_{\mathrm{UE}_2}^{\mathrm{req}}$ are the minimum data rate requirements of the UE_1 and UE_2, respectively; $P_i^{\max}$ is the maximum transmit power budget of node i. Constraints (C1) and (C2) ensure the quality of the end-to-end uplink and downlink transmissions, respectively. Constraint (C3) guarantees that the transmit power of each transmitting node is within the maximum limit.

III. QoS-AWARE POWER CONTROL DESIGN FOR FD RELAY-ENHANCED CELLULAR NETWORKS

P1 is a non-convex optimization problem due to the existence of interference terms in the instantaneous SINRs in (1)-(4), especially the *min* operation in the objective function. Thus, it is extremely difficult to obtain the optimal solutions of P1 directly. In addition, there also exists the feasibility issue in P1 owing to the existence of the minimum spectral efficiency demands of the UEs. Throughout this paper, we assume that the set of per-UE minimum spectral efficiency requirement is feasible under the power constraints of the transmitting nodes, so that we only focus on developing transmit power control scheme.

A. OPTIMAL TRANSMIT POWER

Proposition 1: If P1 is feasible, the optimal transmit power vector $\mathbf{P}^*$ has the following properties: (i) $\mathbf{P}^*$ must have at least one component equal to $P_i^{\max}$. (ii) $\eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}(\mathbf{P}^*) = \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}(\mathbf{P}^*)$ and $\eta_{\mathrm{BS}\to\mathrm{RS}_2}^{\mathrm{DL}}(\mathbf{P}^*) = \eta_{\mathrm{RS}_2\to\mathrm{UE}_2}^{\mathrm{DL}}(\mathbf{P}^*)$ hold.

Proof: (i) Define $\widehat{\mathbf{P}} \triangleq \left(\widehat{P}_{U_1}, \widehat{P}_{R_1}, \widehat{P}_B, \widehat{P}_{R_2}\right)$ as a feasible solution of P1, and $R\left(\widehat{\mathbf{P}}\right) \triangleq C_{\mathrm{UE}_1}^{\mathrm{UL}}\left(\widehat{\mathbf{P}}\right) + C_{\mathrm{UE}_2}^{\mathrm{DL}}\left(\widehat{\mathbf{P}}\right)$ as the objective function of P1. From (1) and (2), for $\alpha > 1$, we have $\eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}\left(\alpha\widehat{\mathbf{P}}\right) = \frac{H_{R_1,U_1}\widehat{P}_{U_1}}{1/\alpha + G_{R_1}\widehat{P}_{R_1} + H_{R_1,B}\widehat{P}_B + H_{R_1,R_2}\widehat{P}_{R_2}} > \eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}\left(\widehat{\mathbf{P}}\right)$ and $\eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}\left(\alpha\widehat{\mathbf{P}}\right) = \frac{H_{B,R_1}\widehat{P}_{R_1}}{1/\alpha + G_B\widehat{P}_B + H_{B,R_2}\widehat{P}_{R_2}} > \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}\left(\widehat{\mathbf{P}}\right)$, hence $C_{\mathrm{UE}_1}^{\mathrm{UL}}\left(\alpha\widehat{\mathbf{P}}\right) > C_{\mathrm{UE}_1}^{\mathrm{UL}}\left(\widehat{\mathbf{P}}\right)$. Similarly, it can be also proven that $C_{\mathrm{UE}_2}^{\mathrm{DL}}\left(\alpha\widehat{\mathbf{P}}\right) > C_{\mathrm{UE}_2}^{\mathrm{DL}}\left(\widehat{\mathbf{P}}\right)$. In summary, we have $R\left(\alpha\widehat{\mathbf{P}}\right) > R\left(\widehat{\mathbf{P}}\right)$. Consequently, the overall spectral efficiency R can be continuously improved by increasing all components of $\widehat{\mathbf{P}}$ by a factor α, until some component P_i hits its maximum transmit power budget $P_i^{\max}$. Therefore, the optimal solution $\mathbf{P}^*$ must have at least one component equal to $P_i^{\max}$.

(ii) Assume that $\mathbf{P}^* \triangleq \left(P_{U_1}^*, P_{R_1}^*, P_B^*, P_{R_2}^*\right)$ is the optimal solution of P1 with $\eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}(\mathbf{P}^*) \neq \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}(\mathbf{P}^*)$. (a) Case 1: $\eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}(\mathbf{P}^*) > \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}(\mathbf{P}^*)$. According to (1) and (2), we can get a feasible solution $\bar{\mathbf{P}} \triangleq \left(\bar{P}_{U_1}, P_{R_1}^*, P_B^*, P_{R_2}^*\right)$ such that $\eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}(\bar{\mathbf{P}}) = \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}(\bar{\mathbf{P}}) = \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}(\mathbf{P}^*)$ with $\bar{P}_{U_1} < P_{U_1}^*$. Thus, we have $C_{\mathrm{UE}_1}^{\mathrm{UL}}(\bar{\mathbf{P}}) = C_{\mathrm{UE}_1}^{\mathrm{UL}}(\mathbf{P}^*)$ according to (5). On the other hand, since the components of $\bar{\mathbf{P}}$ and $\mathbf{P}^*$ are the same except that $\bar{P}_{U_1} < P_{U_1}^*$, we have $\eta_{\mathrm{BS}\to\mathrm{RS}_2}^{\mathrm{DL}}(\bar{\mathbf{P}}) > \eta_{\mathrm{BS}\to\mathrm{RS}_2}^{\mathrm{DL}}(\mathbf{P}^*)$ and $\eta_{\mathrm{RS}_2\to\mathrm{UE}_2}^{\mathrm{DL}}(\bar{\mathbf{P}}) > \eta_{\mathrm{RS}_2\to\mathrm{UE}_2}^{\mathrm{DL}}(\mathbf{P}^*)$ according to (3) and (4). Then, we have $C_{\mathrm{UE}_2}^{\mathrm{DL}}(\bar{\mathbf{P}}) > C_{\mathrm{UE}_2}^{\mathrm{DL}}(\mathbf{P}^*)$ according to (6). As a result, we have $R(\bar{\mathbf{P}}) > R(\mathbf{P}^*)$, which is contradictory to that $\mathbf{P}^*$ is the optimal solution of P1. (b) Case 2: $\eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}(\mathbf{P}^*) < \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}(\mathbf{P}^*)$. According to (1) and (2), as well as the condition for the existence of a positive root of quadratic equations, we can get a feasible solution $\tilde{\mathbf{P}} \triangleq \left(P_{U_1}^*, \tilde{P}_{R_1}, P_B^*, P_{R_2}^*\right)$ such that $\eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}\left(\tilde{\mathbf{P}}\right) = \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}\left(\tilde{\mathbf{P}}\right)$ with $\tilde{P}_{R_1} < P_{R_1}^*$. Moreover, it's readily proven that $\eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}(\mathbf{P}^*) < \eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}\left(\tilde{\mathbf{P}}\right) = \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}\left(\tilde{\mathbf{P}}\right) < \eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}(\mathbf{P}^*)$. Thus, we have $C_{\mathrm{UE}_1}^{\mathrm{UL}}\left(\tilde{\mathbf{P}}\right) > C_{\mathrm{UE}_1}^{\mathrm{UL}}(\mathbf{P}^*)$. On the other hand, since the components of $\tilde{\mathbf{P}}$ and $\mathbf{P}^*$ are the same except that $\tilde{P}_{R_1} < P_{R_1}^*$, we have $\eta_{\mathrm{BS}\to\mathrm{RS}_2}^{\mathrm{DL}}\left(\tilde{\mathbf{P}}\right) > \eta_{\mathrm{BS}\to\mathrm{RS}_2}^{\mathrm{DL}}(\mathbf{P}^*)$ and $\eta_{\mathrm{RS}_2\to\mathrm{UE}_2}^{\mathrm{DL}}\left(\tilde{\mathbf{P}}\right) > \eta_{\mathrm{RS}_2\to\mathrm{UE}_2}^{\mathrm{DL}}(\mathbf{P}^*)$ according to (3) and (4). Then, we have $C_{\mathrm{UE}_2}^{\mathrm{DL}}\left(\tilde{\mathbf{P}}\right) > C_{\mathrm{UE}_2}^{\mathrm{DL}}(\mathbf{P}^*)$ according to (6). As a result, we have $R\left(\tilde{\mathbf{P}}\right) > R(\mathbf{P}^*)$, which is contradictory to that $\mathbf{P}^*$ is the optimal solution of P1.

In summary, the optimal solution $\mathbf{P}^*$ must satisfy that $\eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}(\mathbf{P}^*) = \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}(\mathbf{P}^*)$. Similarly, it can be proven that $\mathbf{P}^*$ also must satisfy that $\eta_{\mathrm{BS}\to\mathrm{RS}_2}^{\mathrm{DL}}(\mathbf{P}^*) = \eta_{\mathrm{RS}_2\to\mathrm{UE}_2}^{\mathrm{DL}}(\mathbf{P}^*)$. ■

B. SP-BASED POWER CONTROL ALGORITHM

To facilitate solving P1, we introduce an auxiliary variable $\mathbf{T} \triangleq (T_1, T_2)$, such that $\min\left(\eta_{\mathrm{UE}_1\to\mathrm{RS}_1}^{\mathrm{UL}}, \eta_{\mathrm{RS}_1\to\mathrm{BS}}^{\mathrm{UL}}\right) \geq T_1$ and $\min\left(\eta_{\mathrm{BS}\to\mathrm{RS}_2}^{\mathrm{DL}}, \eta_{\mathrm{RS}_2\to\mathrm{UE}_2}^{\mathrm{DL}}\right) \geq T_2$. Since the logarithmic function is a monotonic and increasing concave function, P1 can be transformed into the following problem with proper algebraic transformations.

$$
\begin{aligned}
\text{P2:}\ & \min_{\mathbf{T},\mathbf{P}} \prod_{i=1}^{2} \frac{1}{1+T_i} \\
\text{s.t. C1:}\ & \frac{T_1\left(1 + G_{R_1}P_{R_1} + H_{R_1,B}P_B + H_{R_1,R_2}P_{R_2}\right)}{H_{R_1,U_1}P_{U_1}} \leq 1 \\
\text{C2:}\ & \frac{T_1\left(1+G_BP_B+H_{B,R_2}P_{R_2}\right)}{H_{B,R_1}P_{R_1}} \leq 1 \\
\text{C3:}\ & \frac{T_2\left(1+G_{R_2}P_{R_2}+H_{R_2,U_1}P_{U_1}+H_{R_2,R_1}P_{R_1}\right)}{H_{B,R_2}P_B} \leq 1 \\
\text{C4:}\ & \frac{T_2\left(1 + H_{U_2,U_1}P_{U_1} + H_{U_2,R_1}P_{R_1}\right)}{H_{U_2,R_2}P_{R_2}} \leq 1 \\
\text{C5:}\ & T_1 \geq 2^{R_{\mathrm{UE}_1}^{\mathrm{req}}} - 1 \\
\text{C6:}\ & T_2 \geq 2^{R_{\mathrm{UE}_2}^{\mathrm{req}}} - 1 \\
\text{C7:}\ & 0 \leq P_i \leq P_i^{\max},\ \forall i \in \{U_1, R_1, R_2, B\}
\end{aligned} \tag{8}
$$

According to (8), the objective function of P2 is a ratio of a monomial to a polynomial, and all the constraints are polynomials (monomials are also polynomials), such that P2 is a signomial programming (SP) problem [20]. Following the

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Algorithm 1 SP-Based Power Control Algorithm

Input: the normalized channel gain vector $\mathbf{H}$, the normalized residual self-interference channel gain vector $\mathbf{G}$, the minimum data rate requirment vector $\mathbf{R}^{\text{req}}$, and the maximum transmit power budget vector $\mathbf{P}^{\max}$.
Output: $\mathbf{T}$ and $\mathbf{P}$.
Initialize $\mathbf{T}^{(0)}$ and $\mathbf{P}^{(0)}$ by solving a feasibility problem subject to the same constraints as in P2;
Let $\varepsilon = 10^{-4}$ be the error tolerance;
while $\left\|\mathbf{T}^{(k)} - \mathbf{T}^{(k-1)}\right\| > \varepsilon$ **do**
  Update the coefficients $\left\{\beta_{i,n}^{(k)}\right\}$ with (10);
  Approximate the denominator polynomial of the objective function by the monomial $\tilde{f}_i^{(k)}(\mathbf{T})$ with (9);
  Solve the resultant GP problem with the objective function defined by (11) to obtain $\mathbf{T}^{(k)}$ and $\mathbf{P}^{(k)}$;
end

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successive convex approximation approach [21] and the arithmetic-geometric mean inequality [22], P2 can be solved by solving a series of geometric programming (GP) problems subject to the same constraints as in P2, where the GP problem in each iteration is constructed by approximating the denominator polynomial of the objective function by a monomial based on the value of the optimized variable from the previous iteration. To be specific, the denominator polynomial of the objective function in P2 is denoted as $f_i(\mathbf{T}) \triangleq 1+T_i = \sum_{n=1}^{2} u_{i,n}(\mathbf{T})$, where $u_{i,n}(\mathbf{T})$ is a monomial. Then, in iteration k, $f_i(\mathbf{T})$ can be approximated by a monomial $\tilde{f}_i^{(k)}(\mathbf{T})$, that is

$$f_i(\mathbf{T}) \geq \tilde{f}_i^{(k)}(\mathbf{T}) \triangleq \prod_{n=1}^{2} \left(u_{i,n}(\mathbf{T})/\beta_{i,n}^{(k)}\right)^{\beta_{i,n}^{(k)}} \quad (9)$$

with

$$\beta_{i,n}^{(k)} \triangleq u_{i,n}(\mathbf{T}^{(k-1)})/f_i(\mathbf{T}^{(k-1)}) \quad (10)$$

and $\mathbf{T}^{(k-1)}$ denoting the value of $\mathbf{T}$ in iteration $k-1$. Accordingly, the objective function of the GP problem in iteration k is given by

$$\min_{\mathbf{T},\mathbf{P}} \prod_{i=1}^{2}\prod_{n=1}^{2} \left(u_{i,n}(\mathbf{T})/\beta_{i,n}^{(k)}\right)^{-\beta_{i,n}^{(k)}} \quad (11)$$

The iteration is terminated at the loop k if $\left\|\mathbf{T}^{(k)} - \mathbf{T}^{(k-1)}\right\| \leq \varepsilon$, where ε is the predefined error tolerance.

To this end, we devise an SP-based power control algorithm as presented in Algorithm 1. As condensing the objective in the above problem gives us an underestimate of the objective value, each GP in the condensation iteration loop tries to improve the accuracy of the approximation to a particular minimum in the original feasible region. According to Lemma 1 and Propostition 3 in [20], the arithmetic-geometric mean approximation (9) satisfies all three conditions for convergence, such that the condensation method is provably convergent. Moreover, empirically it almost always obtains the globally optimal power allocation [20].

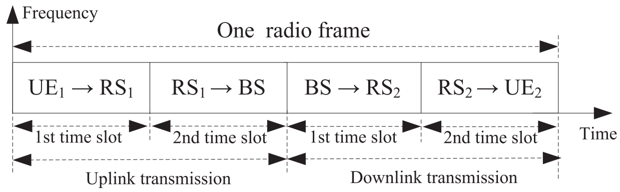

FIGURE 2. Frame structure of the half-duplex relay-enhanced cellular network.

IV. OPTIMAL POWER CONTROL IN HD TRANSMISSION MODE

In the case of HD transmission mode, both the BS and RSs work in HD mode, and we consider time-division based transmission scheme, as shown in Fig. 2. Specifically, the uplink and downlink transmissions take place in two non-overlapping and equal-length time frames. Each time frame consists of two time slots, wherein the source node (e.g., the uplink UE_1 or BS) transmits signal to the relay (e.g., the RS_1 or RS_2) in the first time slot, then the relay forwards the decoded received signal to the destination node (e.g., the BS or downlink UE_2) in the second time slot. In this scenario, there is no interference in the system. Accordingly, the end-to-end spectral efficiencies (bps/Hz) of the uplink and downlink transmissions can be respectively expressed as

$$C_{\text{UE}_1}^{\text{UL\_HD}} = \frac{1}{4}\log\left(1+\min\left(H_{R_1,U_1}P_{U_1}, H_{B,R_1}P_{R_1}\right)\right) \quad (12)$$

$$C_{\text{UE}_2}^{\text{DL\_HD}} = \frac{1}{4}\log\left(1+\min\left(H_{B,R_2}P_B, H_{U_2,R_2}P_{R_2}\right)\right) \quad (13)$$

Note that for a fair comparison, we assume that the duration of the uplink and downlink transmission in the FD mode is normalized to 1, hence that in the HD mode is 1/2. Furthermore, since there are two time slots in the the HD two-hop relaying communications, there is a factor of 1/4 in (12) and (13).

From (12) and (13), the uplink and downlink transmissions are independent from each other, therefore the overall spectral efficiency maximization problem can be decomposed into two subproblems as follows:

$$\text{P3:} \max_{P_{U_1},P_{R_1}} C_{\text{UE}_1}^{\text{UL\_HD}}$$
$$\text{s.t. } C_{\text{UE}_1}^{\text{UL\_HD}} \geq R_{\text{UE}_1}^{\text{req}},\ 0 \leq P_i \leq P_i^{\max},\ \forall i \in \{U_1, R_1\} \quad (14)$$

and

$$\text{P4:} \max_{P_B,P_{R_2}} C_{\text{UE}_2}^{\text{DL\_HD}}$$
$$\text{s.t. } C_{\text{UE}_2}^{\text{DL\_HD}} \geq R_{\text{UE}_2}^{\text{req}}, 0 \leq P_i \leq P_i^{\max}, \quad \forall i \in \{B, R_2\} \quad (15)$$

P3 and P4 are the spectral efficiency maximization problems for the uplink and downlink transmissions, respectively.

In P3, we notice that the function $\min\left(H_{R_1,U_1}P_{U_1}, H_{B,R_1}P_{R_1}\right)$ is a monotonic and increasing function of P_{U_1} and P_{R_1}, and logarithm is a monotonically increasing function. Hence, the objective function of P3 is a monotonic and increasing function with respect to the optimized variables P_{U_1} and P_{R_1}.

As a result, without considering the minimum data rate constraint, P3 has a unique global optimum, and the optimal solution must have at least one component equal to the corresponding maximum transmit power. Moreover, there exists multiple optimal solutions if $H_{R_1,U_1}P_{U_1}^{\max} \neq H_{B,R_1}P_{R_1}^{\max}$. On the other hand, it is worth mentioning that the achievable end-to-end data rate in two-hop relaying communications depends on the smaller one of $H_{R_1,U_1}P_{U_1}^{*}$ and $H_{B,R_1}P_{R_1}^{*}$. If the two terms are not equal to each other, the surplus part of the bigger one is useless for improving the end-to-end data rate, but results in a waste of energy resource. For the sake of the system energy efficiency, we can decrease the corresponding transmit power until the two terms being equal, so as to reduce the overall power consumption while without affecting the achievable end-to-end data rate. Based on the analysis above, we have the following lemma.

Lemma 1: The transmit power $\left\{P_{U_1}^{*}, P_{R_1}^{*}\right\}$ defined by (16) and (17) is an optimal solution of the optimization problem P3 without considering the QoS constraint.

$$P_{U_1}^{*} = \min\left(H_{B,R_1}P_{R_1}^{\max}/H_{R_1,U_1}, P_{U_1}^{\max}\right) \tag{16}$$
$$P_{R_1}^{*} = \min\left(H_{R_1,U_1}P_{U_1}^{\max}/H_{B,R_1}, P_{R_1}^{\max}\right) \tag{17}$$

Proof: Since the objective function of P3 is a monotonic and increasing function with respect to the optimized variables P_{U_1} and P_{R_1}, P3 without the minimum data rate constraint has a unique global optimum, and the optimal solution must have at least one component equal to the corresponding maximum transmit power. Specifically, if $H_{R_1,U_1}P_{U_1}^{\max} \leq H_{B,R_1}P_{R_1}^{\max}$, then we obtain the unique optimal transmit power of the uplink UE_1, i.e., $P_{U_1}^{*} = P_{U_1}^{\max}$, while a range of the optimal transmit power of the RS_1, i.e., $P_{R_1}^{*} \in \left[H_{R_1,U_1}P_{U_1}^{\max}/H_{B,R_1}, P_{R_1}^{\max}\right]$. On the other hand, when $H_{R_1,U_1}P_{U_1}^{\max} > H_{B,R_1}P_{R_1}^{\max}$, we get the unique optimal tranmit power of the RS_1, i.e., $P_{R_1}^{*} = P_{R_1}^{\max}$, while a range of the optimal tranmit power of the uplink UE_1, i.e., $P_{U_1}^{*} \in \left[H_{B,R_1}P_{R_1}^{\max}/H_{R_1,U_1}, P_{U_1}^{\max}\right]$. Clearly, the transmit power defined by (16) and (17) belongs to the resultant optimal solution set. ■

Similarly, we have Lemma 2 for the downlink transmission.

Lemma 2: The transmit power $\left\{P_{B}^{*}, P_{R_2}^{*}\right\}$ defined by (18) and (19) is an optimal solution of the optimization problem P4 without considering the QoS constraint.

$$P_{B}^{*} = \min\left(H_{U_2,R_2}P_{R_2}^{\max}/H_{B,R_2}, P_{B}^{\max}\right) \tag{18}$$
$$P_{R_2}^{*} = \min\left(H_{B,R_2}P_{B}^{\max}/H_{U_2,R_2}, P_{R_2}^{\max}\right) \tag{19}$$

Proof: The proof is similar to that of Lemma 1, hence omitted due to the limited space. ■

Based on Lemma 1 and Lemma 2, we can derive the following Proposition 2 to characterize the properties of the optimal power control scheme for the spectral efficiency maximization problem with QoS guarantees in the HD relaying system.

Proposition 2: In the HD transmission mode, the overall spectral efficiency maximization problem with QoS requirements is feasible if and only if $C_{\mathrm{UE}_1}^{\mathrm{UL\_HD}*}\left(P_{U_1}^{*}, P_{R_1}^{*}\right) \geq R_{\mathrm{UE}_1}^{\mathrm{req}}$ and $C_{\mathrm{UE}_2}^{\mathrm{DL\_HD}*}\left(P_{B}^{*}, P_{R_2}^{*}\right) \geq R_{\mathrm{UE}_2}^{\mathrm{req}}$ with (16)-(19). Moreover, $\mathbf{P}^{*}$ given by (16)-(19) is also the globally optimal solution.

Proof: According to Lemma 1 and Lemma 2, in absence of the minimum data rate constraints, $C_{\mathrm{UE}_1}^{\mathrm{UL\_HD}*}\left(P_{U_1}^{*}, P_{R_1}^{*}\right)$ and $C_{\mathrm{UE}_2}^{\mathrm{DL\_HD}*}\left(P_{B}^{*}, P_{R_2}^{*}\right)$ with (16)-(19) are the maximum achievable end-to-end data rate of the uplink UE_1 and downlink UE_2, respectively. Therefore, it's straightforward that the overall spectral efficiency maximization problem with QoS constraints is infeasible if $C_{\mathrm{UE}_1}^{\mathrm{UL\_HD}*}\left(P_{U_1}^{*}, P_{R_1}^{*}\right) < R_{\mathrm{UE}_1}^{\mathrm{req}}$ or $C_{\mathrm{UE}_2}^{\mathrm{DL\_HD}*}\left(P_{B}^{*}, P_{R_2}^{*}\right) < R_{\mathrm{UE}_2}^{\mathrm{req}}$. Furthermore, if $C_{\mathrm{UE}_1}^{\mathrm{UL\_HD}*}\left(P_{U_1}^{*}, P_{R_1}^{*}\right) \geq R_{\mathrm{UE}_1}^{\mathrm{req}}$ and $C_{\mathrm{UE}_2}^{\mathrm{DL\_HD}*}\left(P_{B}^{*}, P_{R_2}^{*}\right) \geq R_{\mathrm{UE}_2}^{\mathrm{req}}$, it's apparent that $\mathbf{P}^{*}$ given by (16)-(19) is also the globally optimal solution of the overall spectral efficiency maximization problem with QoS constraints. ■

According to Proposition 2, when the QoS requirements can be guaranteed in the HD transmission mode, the spectral efficiency maximization problem with QoS requirements has the same optimal solution as the one without the consideration of the QoS requirements. This is due to the fact that there is no any interference in the system with the time-division based transmission scheme, and hence the uplink and downlink transmissions are independent from each other. However, it's a totally different case for the FD transmission mode, where the uplink and downlink transmissions are tightly coupled through the self-interference as well as the interference among the different links due to concurrent transmissions. This can be verified by the numerical results presented in the next section.

V. PERFORMANCE EVALUATION

To gain insight into the benefits of the FD transmission on network performance, we consider three power control algorithms aiming at maximizing the overall spectral efficiency by jointly optimizing transmit power of the uplink UE, BS and RSs:

- *"FD w. QoS" algorithm*, wherein FD transmission at both the BS and RSs is considered, and the proposed SP-based power control algorithm in Section III-B is employed to maximize the overall spectral efficiency while satisfying diverse QoS requirements of the uplink and downlink UEs.
- *"FD w.o. QoS" algorithm*, which is similar to the "FD w. QoS" algorithm but without considering the QoS constraints of the uplink and downlink UEs.
- *"Conventional HD" algorithm*, wherein HD transmission is considered, and the optimal transmit power proposed in Lemma 1 and Lemma 2 in Section IV is adopted.

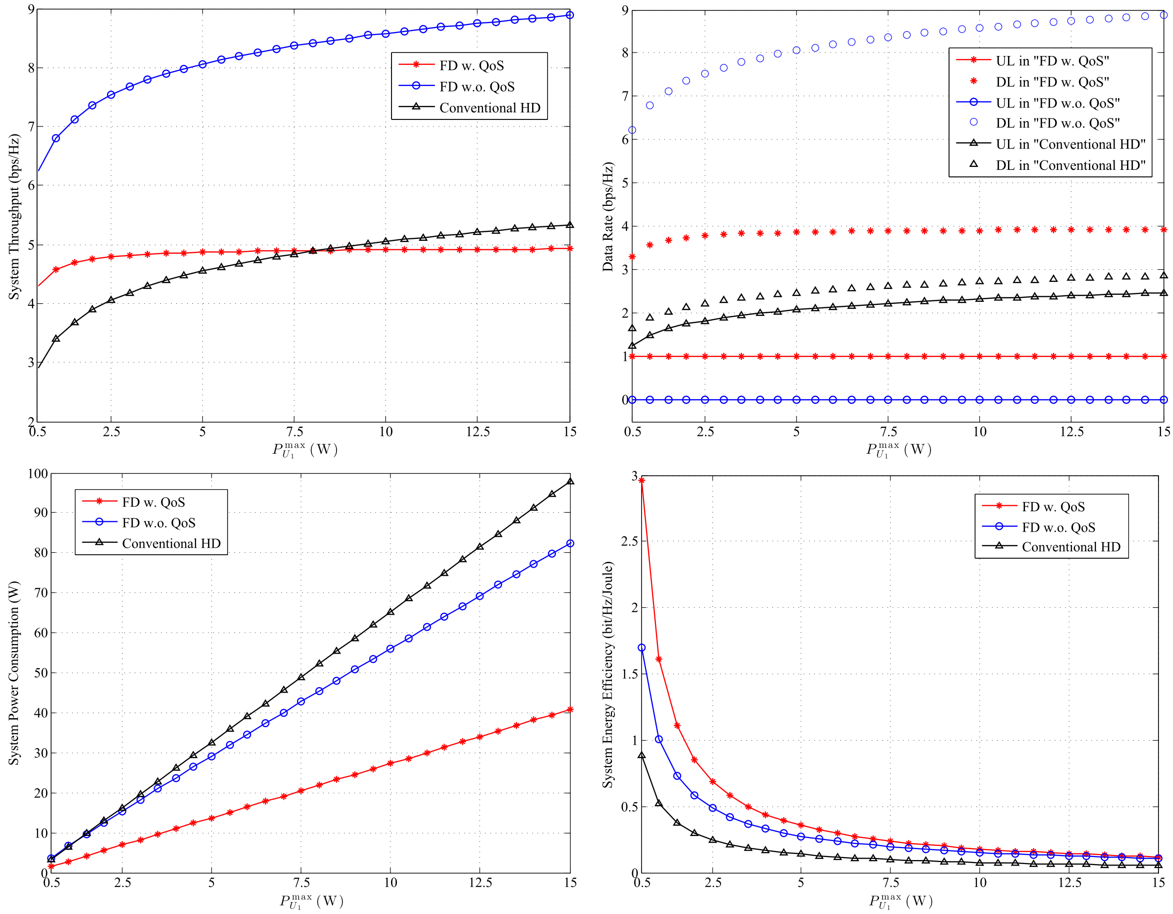

FIGURE 3. (a) System throughput (top-left), (b) per-user data rate (top-right), (c) system power consumption (bottom-left), and (d) system energy efficiency (bottom-right) versus maximum transmit power budget of the uplink UE_1 $P_{U_1}^{\max}$ for different algorithms.

A. EFFECT OF MAXIMUM TRANSMIT POWER CONSTRAINTS

In this section, we study the effect of the maximum transmit power budgets of transmitting nodes on network performance, including system throughput, per-user data rate, total power consumption, and system energy efficiency. In this experiment, we assumed the maximum transmit power budgets of transmitting nodes are $P_{U_1}^{\max} : P_{R_1}^{\max} : P_{B}^{\max} : P_{R_2}^{\max} = 1 : 3 : 5 : 3$ taking into account the differences in their processing capability, and varied $P_{U_1}^{\max}$ from 0.5W to 15W with the increment of 0.5W. In addition, we also made the following assumptions. The minimum data rate requirements of the uplink and downlink UEs are $R_{\mathrm{UE}_1}^{\mathrm{req}} = 1$bps/Hz and $R_{\mathrm{UE}_2}^{\mathrm{req}} = 2$bps/Hz, respectively. The normalized channel gains of the UE-RS (i.e., access link) and BS-RS (i.e., relay link) links are $H_{U_1,R_1} = H_{U_2,R_2} = 18$dB and $H_{B,R_1} = H_{B,R_2} = 20$dB, while that of the interference links are $H_{R_2,U_1} = H_{U_2,R_1} = H_{R_2,R_1} = 3$dB and $H_{U_2,U_1} = 1$dB. The normalized residual self-interference channel gains at the FD nodes are $G_{R_1} = G_{R_2} = G_B = 3$dB.

As shown in Fig. 3 (a), the achievable system throughput of each algorithm improves with the increase of the maximum transmit power budgets of the transmitting nodes, owing to the increasing available energy at each transmitting node. Moreover, the "FD w.o. QoS" algorithm achieves the highest system throughput among the three algorithms. Compared with the conventional HD mode, the FD mode is able to improve the spectral efficiency significantly by transmitting and receiving signals at the same time. It leads to the remarkable superiority of the "FD w.o. QoS" algorithm over the "Conventional HD" algorithm. On the other hand, in the FD mode, the uplink and downlink transmissions interfere with each other, in addition to the residual self-interference at the FD nodes. It makes the achievable data rate in two directions tightly coupled. In this case, in order to fulfill the QoS requirements of the uplink and downlink UEs, the "FD w. QoS" sacrifices a certain amount of system throughput. On the contrary, without the consideration of the QoS constraints of the uplink and downlink transmissions, the "FD w.o. QoS" algorithm achieves the maximum system throughput at the cost of unfairness between the uplink and downlink transmissions. According to the per-user data rate illustrated in Fig. 3 (b), we observe that the uplink UE_1 in the "FD w.o. QoS" algorithm doesn't obtain any service at all, although the downlink UE_2 is allocated with a very high data rate.

From Fig. 3 (a), we also observe that there is an intersection of the two curves of the "FD w. QoS" and "Conventional HD" algorithms. When there is less available transmit power, the "FD w. QoS" algorithm outperforms the "Conventional HD" algorithm on system throughput owing to the improved spectral efficiency achieved by the FD mode. It's worth mentioning that even when the available transmit power is very limited, the "FD w. QoS" algorithm still satisfies the QoS demands of the uplink and downlink UEs, whereas the "Conventional HD" algorithm fails as shown in Fig. 3 (b). When the available transmit power is increased to a certain extent, the "Conventional HD" algorithm begins to overtake the "FD w. QoS" algorithm. This stems from the fact that the sufficient transmit power compensates for the loss of spectral efficiency in the HD mode, whereas the "FD w. QoS" algorithm is restricted by the QoS constraints as well as the uplink-downlink interference and self-interference. As described in Section IV, there is no interference in the time-division based HD system, and hence the uplink and downlink transmissions are independent of each other. In this case, given the channel gains of the access and relay links, the achievable system throughput merely depends on the available transmit power. Consequently, the more the transmit power, the higher the system throughput.

Furthermore, we observe from Fig. 3 (c) that the system power consumption of the "FD w. QoS" algorithm is the lowest, and the growth rate is also the slowest among these three algorithms. In contrast, both the "FD w.o. QoS" and "Conventional HD" algorithms consume power in a relatively aggressive manner. As expected, the system energy efficiency of the "FD w. QoS" algorithm is superior to that of the other two algorithms as illustrated in Fig. 3 (d).

B. EFFECT OF SELF-INTERFERENCE

In this section, we study the effect of the residual self-interference at the FD nodes on system throughput and system power consumption. In this experiment, we assumed the normalized residual self-interference channel gains are $G_{R_1} = G_{R_2} = G_B = \gamma^{\mathrm{SI}}$, and varied γ^{SI} from 0.5dB to 18dB with the increment of 0.5dB. Besides, we also made the following assumptions. The minimum data rate requirements of the uplink and downlink UEs are $R^{\mathrm{req}}_{\mathrm{UE}_1} = 1$bps/Hz and $R^{\mathrm{req}}_{\mathrm{UE}_2} = 2$bps/Hz, respectively. The maximum transmit power budgets are $\left(P^{\max}_{U_1}, P^{\max}_{R_1}, P^{\max}_{B}, P^{\max}_{R_2}\right) = (2, 6, 10, 6)$ W. The normalized channel gains of the UE-RS and the BS-RS links are $H_{U_1,R_1} = H_{U_2,R_2} = 18$dB and $H_{B,R_1} = H_{B,R_2} = 20$dB, while that of the interference links are $H_{R_2,U_1} = H_{U_2,R_1} = H_{R_2,R_1} = 3$dB and $H_{U_2,U_1} = 1$dB.

From Fig. 4 (a) and (b), we observe that both the system throughput and system power consumption of the "FD w. QoS" and "FD w.o. QoS" algorithms decline with the increase of the normalized residual self-interference channel gain γ^{SI}. In contrast, since the "Conventional HD" algorithm is irrelevant to the self-interference, its system throughput and system power consumption remain at a fixed value when varying γ^{SI}. In the FD mode, apparently the larger the γ^{SI}, the higher the self-interference level. In order to mitigate the self-interference and hence improve the quality of signal reception, the FD nodes (e.g., BS or RSs) may reduce their transmit power, resulting in a decrease in data rate of the corresponding links. According to (5) and (6), the achievable end-to-end data rate of the two-hop decode-and-forward relaying communications is limited by the weaker one of the two hops. Moreover, the stronger one of the two hops is useless for improving the end-to-end data rate, but aggravates the interference to the other concurrent transmissions. Thus, the transmitting node of the stronger hop will reduce the transmit power accordingly. Ultimately, it leads to the decrease in the end-to-end data rate and hence the system throughput and system power consumption. As shown in Fig. 4 (a), with the growing self-interference channel gain, the achievable system throughput in the FD mode will eventually fall below that in the HD mode.

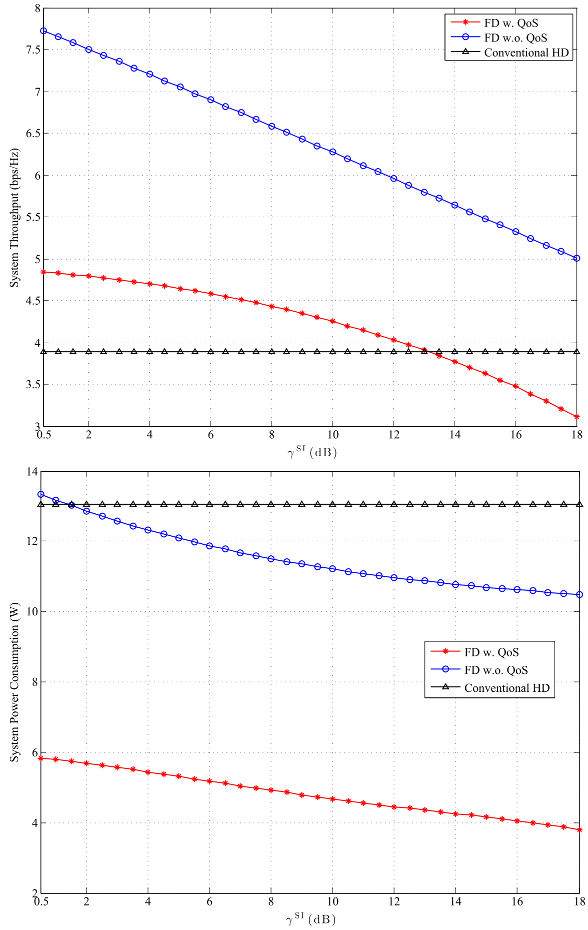

FIGURE 4. (a) System throughput (top) and (b) system power consumption (bottom) versus the normalized residual self-interference channel gain γ^{SI} for different algorithms.

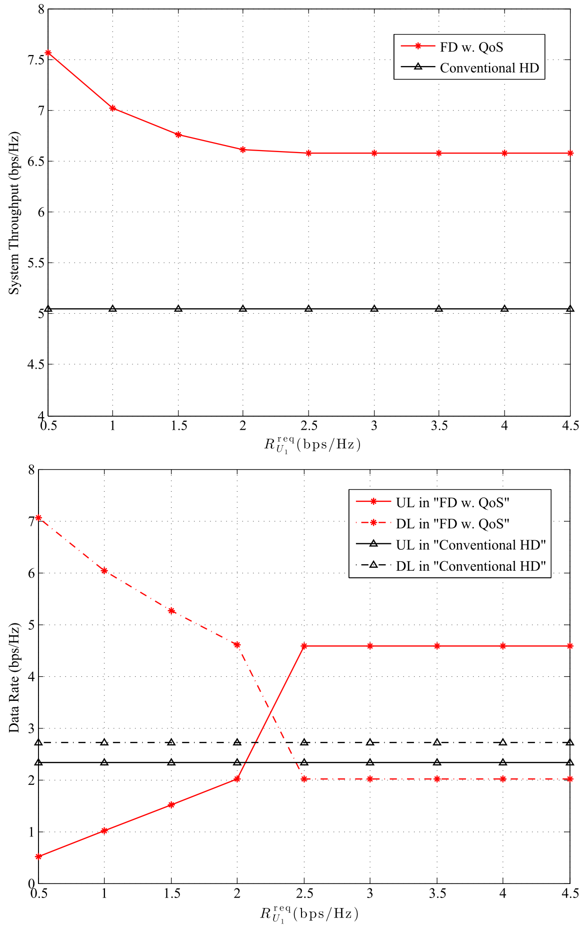

FIGURE 5. (a) System throughput (top) and (b) per-user data rate (bottom) versus the minimum data rate requirement of uplink UE_1 $R_{U_1}^{\mathrm{req}}$ for different algorithms.

C. EFFECT OF MINIMUM QoS CONSTRAINTS

In this section, we study the effect of the minimum data rate requirement of uplink UE_1 on system throughput and the per-user data rate. In this experiment, we fixed the minimum data rate requirement of the downlink UE_2 to $R_{\mathrm{UE}_2}^{\mathrm{req}} = 2$bps/Hz, and varied that of the uplink UE_1 (i.e., $R_{\mathrm{UE}_1}^{\mathrm{req}}$) from 0.5bps/Hz to 4.5bps/Hz with the increment of 0.5bps/Hz. In addition, we also made the following assumptions. The maximum transmit power budgets are $\left(P_{U_1}^{\max}, P_{R_1}^{\max}, P_B^{\max}, P_{R_2}^{\max}\right) = (2, 6, 10, 6)$ W. The normalized channel gains of the UE-RS and BS-RS links are $H_{U_1,R_1} = H_{U_2,R_2} = 25$dB and $H_{B,R_1} = H_{B,R_2} = 28$dB, while that of the interference links are $H_{R_2,U_1} = H_{U_2,R_1} = H_{R_2,R_1} = 3$dB and $H_{U_2,U_1} = 1$dB. The normalized residual self-interference channel gains at the FD nodes are $G_{R_1} = G_{R_2} = G_B = 3$dB.

From Fig. 5 (a), we observe that given the minimum data rate of the downlink UE_2, the system throughput of the "FD w. QoS" algorithm declines with the increase of the minimum data rate requirement of the uplink UE_1, due to the increasing uplink-downlink interference. In the FD mode, the simultaneous uplink and downlink transmissions interfer with each other, and hence their attainable data rate interacts with each other. In this case, increasing one could lead to a decrease in another one. As shown in Fig. 5 (b), the "FD w. QoS" algorithm fulfills the increasing data rate requirement of the uplink UE_1 at the expense of a decrese in data rate of the downlink UE_2. Specifically, when the minimum data rate requirement of the uplink UE_1 is not greater than that of the downlink UE_2, i.e., when $R_{U_1}^{\mathrm{req}} \leq R_{U_2}^{\mathrm{req}}$, the "FD w. QoS" algorithm merely satisfies the minimum demand of the uplink UE_1, whereas provides the downlink UE_2 with a data rate as high as possible, so as to maximize the system throughput while fulfilling the QoS requirements of the UEs. When $R_{U_1}^{\mathrm{req}}$ increases to 2.5bps/Hz, there is an evident leap in the date rate of the uplink UE_1, but on the contrary the data rate of the downlink UE_2 steeps down to the minimum threshold. In our experiment, the "FD w. QoS" algorithm fails to satisfy the QoS demands of the UEs when $R_{U_1}^{\mathrm{req}}$ is equal to 5bps/Hz, but in contrast the outage happens in the "Conventional HD" algorithm since $R_{U_1}^{\mathrm{req}}$ is equal to 2.5bps/Hz. It reveals that the FD mode is more advantageous in providing users with diverse QoS guarantees, thereby improving the quality of experience of users.

D. EFFECT OF UE-RS LINK QUALITY

In this section, we study the effect of the normalized channel gain of the UE-RS links on system throughput and per-user data rate. In this experiment, we assumed the normalized channel gains of the UE-RS links are $H_{U_1,R_1} = H_{U_2,R_2} = \gamma^{\text{UE - RS}}$, and varied $\gamma^{\text{UE - RS}}$ from 15dB to 75dB with the increment of 5dB. Besides, we also made the following assumptions. The normalized channel gains of the BS-RS links are $H_{B,R_1} = H_{B,R_2} = 25$dB. The minimum data rate requirements of the uplink and downlink UEs are $R_{\mathrm{UE}_1}^{\mathrm{req}} = 1$bps/Hz and $R_{\mathrm{UE}_2}^{\mathrm{req}} = 2$bps/Hz, respectively. The maximum transmit power budgets are $\left(P_{U_1}^{\max}, P_{R_1}^{\max}, P_B^{\max}, P_{R_2}^{\max}\right) = (2, 6, 10, 6)$ W. The normalized channel gains of the interference links are $H_{R_2,U_1} = H_{U_2,R_1} = H_{R_2,R_1} = 2$dB and $H_{U_2,U_1} = 1$dB. The normalized residual self-interference channel gains at the FD nodes are $G_{R_1} = G_{R_2} = G_B = 1$dB.

As shown in Fig. 6 (a), the system throughput of each algorithm improves firstly and then tends to be stable with the increase of $\gamma^{\text{UE - RS}}$, given the normalized channel gains of the BS-RS links. It is straightforward that the enhanced link quality is conducive to improve the achievable end-to-end data rate and hence the system throughput. On the other hand, since the weaker hop is the bottleneck for the achievable end-to-end data rate of the two-hop decode-and-forward relay communications, the end-to-end data rate of the uplink and downlink transmissions and hence the system throughput becomes saturated when $\gamma^{\text{UE - RS}}$ is increased to a certain value. More importantly, we observe from Fig. 6 (a) that the algorithms with FD mode are evidently superior to the one with HD mode, owing to the enhanced spectral efficiency achieved by FD mode. Furthermore, the gap between the "FD w. QoS" and "FD w.o. QoS" algorithms is shrinking and becomes zero eventually as $\gamma^{\text{UE - RS}}$ increases.

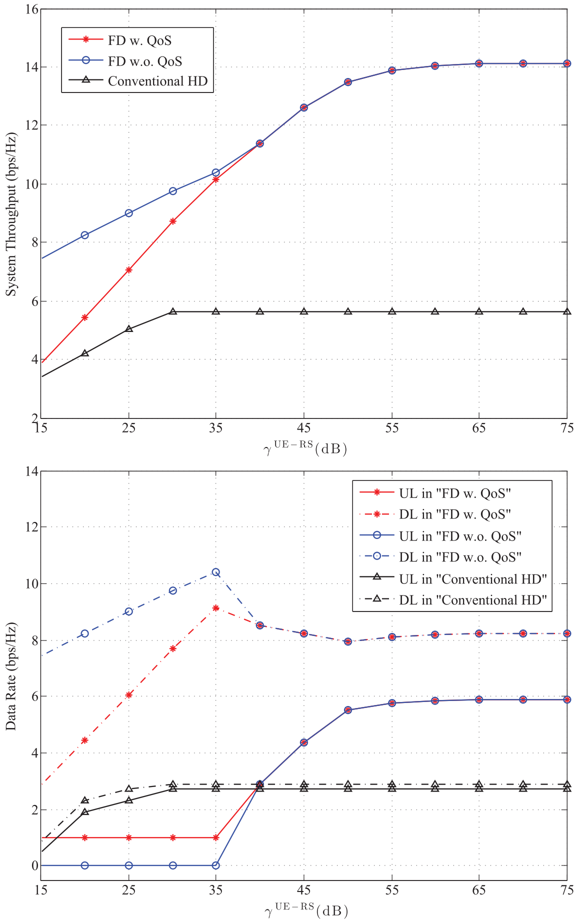

FIGURE 6. (a) System throughput (top) and (b) per-user data rate (bottom) versus the normalized channel gain of the UE-RS links $\gamma^{\text{UE - RS}}$ for different algorithms.

It implies that when the link quality is improved to a certain extend, the QoS constraints are met inherently even in the "FD w.o. QoS" algorithm, and moreover the "FD w. QoS" and "FD w.o. QoS" algorithms have the same optimal solutions, thereby achieving the same system throughput.

Although the system throughput improves with the increase of $\gamma^{\text{UE - RS}}$ as illustrated in Fig. 6 (a), we observe from Fig. 6 (b) that the data rate of the uplink and downlink UEs in the algorithms with FD mode experiences the different trends due to the changing link quality and interference environment. At the beginning, the uplink UE_1 is only allocated with a data rate of the minimum demand in the "FD w. QoS" algorithm and zero in the "FD w.o. QoS" algorithm. On the contrary, the data rate of the downlink UE_2 improves significantly with the increase of $\gamma^{\text{UE - RS}}$ in both algorithms. When $\gamma^{\text{UE - RS}}$ is increased to 40dB, there is an evident improvement on the data rate of the uplink UE_1, and a certain amount of decrease in that of the downlink UE_2. Ultimately, the data rate of both the uplink and downlink UEs becomes stable.

VI. CONCLUSION

In this paper, we studied QoS-aware interference mitigation for the FD relay-enhanced cellular networks to address the residual self-interference, the uplink-downlink interference, and the relay-access-link interference. Specifically, we formulated the power control design as a non-convex optimization problem, with the objective of maximizing the system spectral efficiency subject to the QoS requirements of the uplink and downlink UEs as well as the individual power constraints of the uplink UE, BS, and RSs. We characterized the properties of the optimal transmit power allocation, and developed a SP-based power control algorithm to obtain the globally or at least locally optimal power allocation. In addition, we also derived the closed-form optimal transmit power allocation for the spectral efficiency maximization problem in the HD transmission mode. We conducted extensive simulation experiments to study the effects of the different factors on system performance. Simulation results demonstrate that FD relaying can achieve higher the spectral and energy efficiency than HD relaying, and also has better QoS provisioning ability. Our results provide important guidelines for designing full-duplex networks.

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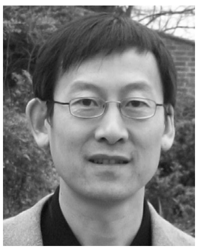

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