Statistical QoS Aware for Wireless Powered Cooperative Communications in Internet of Things

YA GAO (Member, IEEE), YONGPENG SHI (Member, IEEE), YUJIE XIA (Member, IEEE), AND HAILIN ZHANG (Member, IEEE)

1School of Physics and Electronic Information, Luoyang Normal University, Luoyang 471934, China
2Henan Key Laboratory for Big Data Processing and Analytics of Electronic Commerce, Luoyang Normal University, Luoyang 471934, China
3State Key Laboratory of Integrated Services Networks, Xidian University, Xi’an 710071, China

Corresponding author: Ya Gao (gaoya@lynu.edu.cn)

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ABSTRACT This article unveils the importance of statistical quality of service (QoS) for resource allocation in a two-hop network. Particularly, an access point (AP) serves multiple IoT devices for information transfer with the assistance of the energy harvesting (EH) relaying. To explore the maximum constant data arrival metric, we aim to maximize the effective capacity (EC) under specified QoS requirements. Also, the statistical QoS inspired resource allocation policies are investigated for half/full duplex (HD/FD) modes, respectively, to jointly optimize power allocation and power splitting (PS) ratio. To solve the formulated problem, we first derive the closed-form solution of the optimal power allocation at the AP and the PS ratio. To gain more insights, we further derive the boundary conditions of optimal power allocation and PS ratio. Finally, numerical results are demonstrated to validate the theoretical derivations, which highlights the proposed scheme in terms of EC performance in comparison to the benchmark scheme.

INDEX TERMS Internet of Things networks, simultaneous wireless information and power transfer, statistical QoS, relay communications, power allocation.

I. INTRODUCTION

With the advance of fifth generation (5G) communication networks, the wireless devices have been employed for numerous applications, i.e., sensor detection [1]–[3]. The application boosting of wireless devices brings a large consumption of energy, thus, leading to the energy scarcity [4]. Conventionally, some energy conservation technologies, i.e., energy minimization, studied to prolong the wireless devices’ life-time and extend the networks operating-time [5], [6]. Although these technologies allow proper utilizing the available energy, the energy conservation may still reduce the network performance. Nevertheless, the energy shortage in wireless communications networks remains a performance bottleneck due to lack of sustainable energy supply, enabling the battery-replacement necessary. Moreover, the explosive increase of wireless communications technologies also promotes the emergence of Internet of Things (IoT), which will affect all aspects of people’s daily life in many scenarios, such as medical observation, military surveillance, regional monitoring and so on [7]–[9]. In some of these cases, replacing battery can be very dangerous or even impossible. Thus, with the vigorous expansion of IoT, the aforementioned issues should be taken more seriously.

As a prominent solution, energy harvesting unlocks a novel potential of wireless devices collecting energy from the surrounding energy sources, i.e., solar photovoltaic generation, thermoelectric generator device, wind generator, etc, which can provide the sustainable energy supply [10]–[12]. However, harvesting energy from these natural energy sources is usually intermittent and unstable. To maintain an everlasting and reliable energy supply for IoT networks, a more
controllable energy harvesting method, radio frequency (RF) radiation, is employed to supply energy for IoT devices, which is called wireless power transfer. Wireless power transfer technology has drawn variety of significant research attentions, and has been integrated in various wireless communications such as cognitive radio networks [13], [14], wireless sensor networks [15], and mobile edge computing networks [16] and so on. As a wireless power transfer technology, Simultaneous Wireless Information and Power Transfer (SWIPT), enabling simultaneously wireless information decoding and RF energy harvesting, which can potentially prolong the life time of wireless devices to circumvent interruption of the data transmission [17]. To achieve simultaneously information and wireless power transfer, two energy harvesting policies have been introduced: Power Switching (PS) [18] and Time Switching (TS) [19]. Most literatures concerning SWIPT focus on the half duplex transmission [20]. However, how to further improve the spectrum efficiency is still lack of attention. Full duplex, allowing communications in two directions, can be exploited much more efficiently [21]–[23]. Thus, integrating full duplex transmission with SWIPT, which can not only extend the lifetime of wireless devices but also improve the spectrum efficiency, is very promising [24], [25].

The IoT networks have been widely used in long distance and wide coverage wireless communications scenarios. Relaying communications, as it can expand the communications coverage, decrease energy consumption, and improve network capacity, has been extensively studied in recent years [26]–[28]. For relaying communications, the source transmits data information to destination devices by the assistance of relay. Two main relay forward strategies are always adopted, decode-and-forward (DF) [29] and amplify-and-forward (AF) [30]. Combining wireless power transfer with relaying communications has attracted the interests of researchers since it takes full advantage of the two policies.

Moreover, future communications networks require to deal with a huge of diverse multimedia traffic, which are expected to provide wireless services with diverse Quality of Service (QoS) guarantees, especially for the IoT networks [31], [32]. However, due to the time-varying and space-varying nature of the wireless channels, it is considerably difficult to deterministically guarantee the QoS requirements for wireless communications networks [33]. Thus, statistical QoS assurance has become an important alternative metric to provide the required quality and performance for wireless communications. Combining information theory with specified statistical QoS guarantees, the theory of effective capacity (EC) has drawn an amount of attentions. The authors in [34] developed a statistical QoS supported power control policy for D2D and cellular communications coexisting networks. The authors of [35] employed the heterogeneous statistical QoS to characterize the real-time services for mobile airborne wireless networks. The author of [36] analyses the statistical QoS constraints for fading channels. The authors of [37] and [38] studied statistical QoS provision mechanism for edge network slicing and 5G green networks. To the best of our knowledge, few of research work focus on the statistical QoS assurance for wireless powered relay enabled IoT networks.

In this article, we unveil the importance of the statistical QoS for resource allocations in wireless powered relay based IoT networks. Specifically, we consider a two-hop IoT network model, where the wireless powered relay node simultaneously decode data information and harvest energy from access point. First, we exploit the half/full duplex transmission modes, and conduct the statistical QoS scheduling, respectively. Then, effective capacity maximization problems are formulated in half duplex mode and the statistical QoS guaranteed optimal joint access point power control policies and power splitting ratio schemes are obtained. To further improve the performance of the wireless powered relay based IoT networks, we study the optimal resource allocation schemes under full duplex mode, which can potentially improve the network capacity by allowing the simultaneous information reception and transmission. This also results in a serious self-interference. We introduce a self-interference elimination coefficient to characterize the self-interference at relay node. By exploiting the optimal resource allocation schemes under half/full duplex modes, we gain more insights for its boundary condition. Finally, numerical results are demonstrated to confirm the effect of statistical QoS requirements and self-interference cancellation coefficient on our proposed resource allocation schemes.

The remainder of the paper is organized as follows. Section II presents the wireless powered relay based IoT networks models and analyses the corresponding statistical QoS aware mechanisms. Section III and Section IV optimize the joint access point power allocation and power splitting ratio policies under half/full duplex modes, respectively, to maximize the EC. Section V simulates our investigated statistical QoS supporting resource allocation schemes for wireless powered relay based relay networks. Section VI gives the conclusions.

II. THE SYSTEM MODEL

A. THE WIRELESS POWERED RELAY BASED IoT NETWORK MODEL

We consider a two-hop IoT networks, as depicted in Fig. 1, where the access point (AP) intends to transmit information to the IoT device. Due to the long distance between the AP and IoT device, the direct link between them is negligible. Thus, a wireless powered relay is disposed to forward the data information transmission from AP to IoT device. The decode-and-forward (DF) strategy is adopted at the relay node. Assuming that the relay node has little energy supply and only depends on the RF wireless power transfer from the AP.

As shown in Fig. 1, at each wireless node and device, the data packets in buffers are decomposed into frames at the data link layer, and then divided into bitstreams at the...
physical layer. There are two kinds of links in this considered two-hop IoT networks, i.e., access point to relay node link, denoted by A-to-R, and relay node to IoT device link, denoted by R-to-I. The channel state information (CSI) is assumed to be correctly calculated at the relay/IoT nodes and reliably responded to the corresponding transmitters, respectively. Based on the corresponding links CSI and the real-time traffic determined delay-bounded QoS constraint, the access point and relay node should optimize the resource allocation policies to maximize the network throughput under the statistical delay-bounded QoS requirement.

B. CHANNEL MODEL

We make the assumption that both A-to-R and R-to-I links are quasi-static channels. The corresponding channel gains follow the stationary block fading model, which indicates that the channel gains remain unchanged in one frame time length $T_f$, but independently vary among different frames [39]. Let us denote $|h_1|^2$ and $|h_2|^2$ the A-to-R and R-to-I links channel gains, respectively. $N_1$ and $N_2$ denote the channel noise of A-to-R and R-to-I links, respectively. Then, the corresponding CSI is represented as $\gamma_1 = |h_1|^2/N_1$ and $\gamma_2 = |h_2|^2/N_2$. Moreover, the distance between access point and IoT device is normalized to be one. The distance between access point and relay node is denoted by $s(0 < s < 1)$. Thus, the distance between IoT device and relay is $1 - s$. We employ the exponential fading channel model with the parameters $\lambda_1$ and $\lambda_2$ for A-to-R and R-to-I links. We denote the corresponding wireless channel probability density $p_T(\gamma_1)$ and $p_T(\gamma_2)$, respectively, which are written as follows:

$$p_T(\gamma_j) = \lambda_j e^{-\lambda_j \gamma_j}, \quad j \in \{1, 2\},$$

where $\lambda_j (j \in \{1, 2\})$ is determined by $\lambda_1 = s^\alpha$ and $\lambda_2 = (1 - s)^\alpha$. Here $\alpha$ is the path loss exponent.

C. WIRELESS POWERED RELAY

Power Splitting (PS) protocol is adopted at the wireless powered relay node to simultaneously transmit power and data information. We denote $\rho$ the PS ratio, which indicates that a part $\rho$ of the received radio frequency signal power at relay node is used for information decoding while the other $1 - \rho$ for energy harvesting. Let us denote $P_a$ the transmit power of access point and $P_r$ the transmit power of relay, respectively. The receiving noise interference at the relay is neglected. Then, based on the law of energy conservation, the relay node transmit power can be presented as follows:

$$P_r = (1 - \rho)\eta \gamma_1 P_a,$$

where $\eta(0 < \eta < 1)$ is the power conversion coefficient. The wireless powered relay based IoT network is assumed to
be average power limited. Then, the transmit power at access point and relay node need to satisfy
\[ \mathbb{E}_\gamma [P_a + P_r] \leq \bar{P}, \] (3)
where \( \mathbb{E}_\gamma [\cdot] \) represents the expectation with respect to \( \gamma \) and \( \bar{P} \) denotes the mean transmit power threshold.

### D. Transmission Modes

There are two kinds of basic transmission modes for wireless powered relay based IoT networks, i.e., half duplex and full duplex. Transmission rates for half duplex communications and full duplex communications are quite different from each other.

1) **HALF DUPLEX MODE**

For half duplex wireless powered relay based IoT networks, each frame is separated into two equal parts, while the energy harvesting phase at the relay occupies the first half of each frame and the remaining half of each frame duration is used to forward information to IoT device, which corresponds to information transmission phase. Since DF protocol is adopted, the transmission rate for wireless powered relay based IoT networks with half duplex mode, denoted by \( R_h \), is presented as follows
\[ R_h = \frac{B T_f}{2} \min \{ \log_2(1 + \rho \gamma_1 P_a), \log_2(1 + \gamma_2 P_r) \}. \] (4)

In Eq. (4), \( B \) denotes the system bandwidth. Eq. (4) indicates the achievable transmission rate of half duplex wireless powered relay based IoT networks is the minimum transmission rate of the A-to-R link and R-to-I link. The access point uses the transmit power of \( P_a \) in the first half of each frame while the relay sends data information with the power of \( P_r \) in the second half of frame duration. Substitute Eq. (2) into Eq. (4). Then, \( R_h \) can be rewritten as
\[ R_h = \frac{B T_f}{2} \min \{ \log_2(1 + \rho \gamma_1 P_a), \log_2(1 + (1 - \rho) \eta \gamma_1 \gamma_2 P_a) \}. \] (5)

2) **FULL DUPLEX MODE**

Employing full duplex mode, relay node harvests energy and transmits data information simultaneously, which may cause the self-interference between transceiver antennas due to the signal leakage [40], [41]. There exists two self-interference cancellation strategies for characterizing the self-interference in full duplex transmission mode: self-interference depending on transmission power and independent on transmission power [42]. In this article, we apply the latter model by introducing a control parameter to describe the full duplex self-interference cancellation. We denote \( \xi \ (0 < \xi \leq 1) \) the full duplex self-interference parameter. Also, \( C_f \) denotes the channel capacity for full duplex mode. Then, the expression of \( C_f \) is shown as follows
\[ C_f = \log_2 (1 + \xi \text{SNR}), \] (6)

where \( \text{SNR} \) represents the signal to noise ratio at relay. In Eq. (6), full duplex self-interference cancellation parameter \( \xi \) is related to some aspects, such as arrangement of transceiver antenna array, signals amplitude and so on. A small value of \( \xi \) (i.e., \( \xi \) approaches 0) indicates a large self-interference on relay node transmission. A large value of \( \xi \) (i.e., \( \xi \) is up to 1) represents little self-interference caused on relay node transmission. Thus, when \( \xi \) is equivalent to 1, full duplex transmission mode is reduced to half duplex transmission mode.

Since decode-and-forward strategy is employed on the relay node, the achievable rate for wireless powered relay based IoT networks for full duplex mode, denote by \( R_f \), is derived as follows
\[ R_f = B T_f \min \{ \log_2(1 + \xi \rho \gamma_1 P_a), \log_2(1 + \gamma_2 P_r) \}, \]
\[ = B T_f \min \{ \log_2(1 + \xi \rho \gamma_1 P_a), \log_2(1 + (1 - \rho) \eta \gamma_1 \gamma_2 P_a) \}. \] (7)

By introducing the cancelation coefficient, the achievable rate can be transformed to a convex function. Thus, in the following problem formulation and solution, mathematical manipulation can be simplified.

### E. Statistical QoS-Aware Mechanism

Since wireless channels are time-varying, it is difficult to deterministically provide the QoS guarantees. To characterize the time-varying nature, we employ a statistical QoS metric, which is the delay violation probability for describing the probability that the traffic delay exceeds a given threshold, for delay sensitive traffics.

On the basis of Large Derivation Principle, Chang has provided that [43], the process of queue length approaches to a finite variable \( Q(\infty) \), which needs to satisfy
\[ -\lim_{q \to \infty} \frac{\log \Pr(Q(\infty) \geq q)}{q} = \theta, \] (8)
where \( q \) denotes the given queue length threshold and \( \theta \) (\( \theta > 0 \)) represents the QoS exponent. Eq. (8) illustrates that the probability of the queue length beyond the threshold \( q \) attenuates exponentially as fast as \( q \) increases. Thus, we can obtain the probability that the queue length \( Q(t) \) exceeds the threshold \( q \) as follows
\[ \Pr(Q(t) > q) \simeq \exp(-\theta q). \] (9)

Moreover, if we consider the delay queue associated delay QoS exponent, according to Eq. (9), the delay bounded violation probability can be presented as follows
\[ \Pr(\tau > t_0) \simeq \exp(-\delta t_0), \] (10)
where \( t_0 \) is the delay bound and \( \delta \) can be calculated based on the arrival and service processes [43]. Based on the above analyses, we can find that the QoS exponent is an important metric for statistical QoS provisioning. Large value of \( \theta \) means that the corresponding delay-sensitive traffic has a
stringent QoS requirement. By contrast, small value of $\theta$ indicates that a loose QoS demand can be supported.

Combining statistical QoS with information theory, the authors of [44] investigate effective capacity (EC), which is defined as the maximal arrival rate that a certain service process can support under a specific QoS requirement. We denote $R[i]$ a stationary and ergodic stochastic service process during discrete time $\{i = 1, 2, \ldots\}$. Then, the partial sum of $R[i]$ is denoted by $S[i] = \sum_{i=1}^{\infty} R[i]$, and the Gärtner-Ellis limit of which is defined as

$$\Lambda_C(\theta) = \lim_{t \to \infty} \left( \frac{1}{t} \right) \log \mathbb{E}[e^{\theta S[t]}].$$

Eq. (11) is convex with respect to real QoS exponent $\theta$ [43]. Then, the EC for wireless powered relay based IoT networks, denoted by $C$, is written as follows [44]:

$$\bar{C}(\theta) = -\frac{\Lambda_C(-\theta)}{\theta} = -\frac{1}{\theta} \log \left( \mathbb{E} \left[ e^{-\theta R[i]} \right] \right).$$

Observing Eq.(12), we find that the EC for wireless powered relay based IoT networks referred to as throughput under the statistical delay-bounded QoS guarantees. Introducing the statistical delay-bounded QoS metric $\theta$, we can formulate a novel problem, which is an EC maximization problem for wireless powered relay based IoT networks.

III. QoS GUARANTEED OPTIMAL RESOURCE ALLOCATION FOR WIRELESS POWERED RELAY BASED IoT NETWORKS UNDER HALF DUPLEX MODE

In this section, to maximize the effective capacity for wireless powered relay based IoT networks, we jointly optimize the statistical QoS guaranteed transmission power control policies and power splitting ratio allocation schemes. Conventionally, the optimal power control scheme is a function of instantaneous channel state information $\gamma$. However, for wireless powered relay based IoT networks, the statistical QoS guaranteed optimal power control policies and optimal power splitting ratio allocation schemes can be expressed as a function of statistical delay-bounded QoS requirement $\theta$ and channel state information $\gamma$. Thus, for simply description, we denote $\mu = (\theta, \gamma)$ the statistical QoS aware half duplex network state information (NSI) for IoT networks with wireless powered relay.

A. EFFECTIVE CAPACITY MAXIMIZATION UNDER HALF DUPLEX MODE

Let us denote $P_{ah}$ and $\rho_h$ the power control policy and power splitting ratio for half duplex wireless powered relay based IoT networks, respectively. We formulate the EC maximization problem for half duplex wireless powered relay based IoT networks, subject to the mean power constraints, which is shown as follows

$$P(1) : \arg \max_{P_{ah}(\mu), \rho_h} \left\{ \frac{1}{\theta} \log \left( \mathbb{E}_\gamma \left[ \exp(-\theta R_h(\mu)) \right] \right) \right\}$$

s.t. : 1). $\mathbb{E}_\gamma [P_{ah}(\mu) + (1 - \rho_h)\eta\gamma_1P_{ah}] \leq P$; (13)

2). $P_{ah}(\mu) \geq 0$; (14)

3). $0 < \rho_h < 1.$

Jointly optimizing the access point power control policies $P_{ah}$ and power splitting ratio $\rho_h$, we can maximize the EC with statistical QoS-aware for half duplex wireless powered relay based IoT networks. We simplify the problem $(P1)$ by substituting Eq. (5) into the objective function of $(P1)$, which is written as follows

$$(P1') : \arg \max_{P_{ah}(\mu), \rho_h} \left\{ \frac{1}{\theta} \log \left( \mathbb{E}_\gamma \left[ \max \{1 + \rho_h\gamma_1P_{ah}(\mu)\} \right] \right) \right\}$$

s.t. : Eq. (13) – (15).

The equation $(a)$ in problem $(P1')$ is satisfied because the objective function in problem $(P1')$ is convex. $A_1(\mu)$ and $A_2(\mu)$ in problem $(P1')$ is shown as follow

$$A_1(\mu) = (1 + \rho_h\gamma_1P_{ah}(\mu))^{-\beta},$$

$$A_2(\mu) = (1 + (1 - \rho_h)\eta\gamma_1\gamma_2P_{ah}(\mu))^{-\beta},$$

where $\beta$ denotes the normalized QoS exponent and is equivalent to $(\theta T_1 B)/\log 2$. Since $A_1(\mu)$ and $A_2(\mu)$ are both convex function, the maximization of $A_1(\mu)$ and $A_2(\mu)$, which is the pointwise supremum of $A_1(\mu)$ and $A_2(\mu)$, is also convex. Thus, problem $(P1')$ is convex. Based on the work of [18], for half duplex wireless powered relay based IoT networks, the optimal resource allocation schemes need satisfy that

$$A_1(\mu) = A_2(\mu).$$

Then, we can equivalently convert problem $(P1')$ into $(P1'')$, which is shown as follow

$$P(1'') : \arg \min_{P_{ah}(\mu), \rho_h} \left\{ \mathbb{E}_\gamma \left[ (1 + \rho\gamma_1P_{ah}(\mu))^{-\beta} \right] \right\}$$

s.t. : Eq. (13) – (15).

Since the objective function of problem $(P1'')$ is convex and the constraints are all linear, the problem $(P1'')$ is convex optimization problem, thus existing a unique optimal solution.

B. OPTIMAL RESOURCE ALLOCATION SCHEMES UNDER HALF DUPLEX MODE

Solving the effective capacity maximization problem for wireless powered relay based IoT networks under half duplex mode, we can obtain the delay-bounded statistical QoS guaranteed joint optimal power control policy and the optimal power splitting ratio, denoted by $P_{oh}(\mu)$ and $\rho_h^*$, which is shown in Theorem 1.

**Theorem 1:** For wireless powered relay based IoT networks with half duplex transmission, the statistical QoS provisioning optimal joint access point power control policy and
power splitting ratio allocation scheme is given by
\[
P_{ah}(\mu) = \begin{cases} 
1 & \text{if } \gamma \geq \gamma_{th1}; \\
\rho_h \frac{\gamma \eta}{1 + \gamma \eta} & \text{if } \gamma < \gamma_{th1};
\end{cases}
\]
where \(\gamma_{th1}\) denotes the cutoff SNR threshold. We can numerically calculate \(\gamma_{th1}\) by substituting Eq. (19) into
\[
\int_{0}^{\infty} \int_{0}^{\infty} \left[ P_{ah}^s + (1 - \rho_h^s)\eta \gamma_1 P_{ah}^s \right] p_{\Gamma}(\gamma_1)p_{\Gamma}(\gamma_2)d\gamma_1d\gamma_2 = P.
\]
(20)

Proof 1: As mentioned above, problem \((P1''')\) is convex. Thus, there exists a unique optimal solution. We denote the Lagrangian function of problem \((P1'')\) by \(J_1\), which is built as follows
\[
J_1 = \mathbb{E}_\gamma \left[ (1 + \rho_h \gamma_1 P_{ah}^{-\beta}) \right] + \lambda \left[ \mathbb{E}_\gamma [P_{ah} + (1 - \rho_h)\eta \gamma_1 P_{ah}] - P \right].
\]
(21)
where \(\lambda\) denotes the Lagrangian multiplier. Employing Karush-Kuhn-Tucker (KKT) conditions, we can obtain
\[
\frac{\partial J_1}{\partial P_{ah}} = - \beta (1 + \rho_h \gamma_1 P_{ah})^{-\beta-1} \rho_h \gamma_1 \beta (\gamma)_1 + \lambda [1 + (1 - \rho_h)\eta \gamma_1] \beta (\gamma)_1 = 0.
\]
(22)
Solving Eq. (22), we can derive \(P_{ah}^*\) in Theorem 1. Then, substituting it to \(A_1(\mu)\) and \(A_2(\mu)\) in Eq. (17) and setting \(A_1(\mu) = A_2(\mu)\), we can obtain \(\rho_h^*\) in Theorem 1. \(\gamma_{th1}\) is the SNR threshold. Then, we plug Eq. (19) into \(\mathbb{E}_\gamma [P_{ah}(\mu) + (1 - \rho_h)\eta \gamma_1 P_{ah}] = P\), and \(\gamma_{th1}\) can be numerically derived.

Theorem 1 gives the optimal statistical delay-bounded QoS aware joint access point power control strategy and power splitting ratio for wireless powered relay based IoT networks. To further compare the performance between half duplex mode and full duplex mode, we study the optimal resource allocation schemes under full duplex mode.

### IV. QoS Guaranteed Optimal Resource Allocation for Wireless Powered Relay Based IoT Networks Under Full Duplex Mode

Different from half duplex mode, the full duplex mode enables the wireless powered relay to harvest energy and transmit data information simultaneously, thus, leading to self-interference between transceiver antennas at the relay node. For wireless powered relay based IoT networks, the statistical QoS guaranteed joint optimal power control policy and power splitting ratio is associated with not only statistical QoS exponent \(\theta\) and channel state information \(\gamma\), but also self-interference coefficient \(\zeta\). Then, we denote \(v = (\zeta, \theta, \gamma)\) the NSI for statistical QoS guaranteed full duplex wireless powered relay based IoT networks.

### A. Effective Capacity Maximization Under Full Duplex Mode

For wireless powered relay based IoT networks with full duplex mode, we optimize the optimal access point power control policy, denoted by \(P_{af}^*\), and power splitting ratio, denoted by \(\rho_f^*\), to maximize the effective capacity under the mean power constraint, which is shown as follows
\[
(P2) : \arg \max_{P_{af}(v), \rho_f} \left\{ -\frac{1}{\theta} \log (\mathbb{E}_v [\exp(-\theta R_i(v))]) \right\} = \begin{cases} 
(b) \arg \min_{P_{af}(v), \rho_f} \left\{ \mathbb{E}_v \left[ \max(A_3(v), A_4(v)) \right] \right\} \\
(c) \arg \min_{P_{af}(v), \rho_f} \left\{ \mathbb{E}_v \left[ A_3(v) \right] \right\}
\end{cases}
\]
(23)
\[
s.t.: 1). \mathbb{E}_v [P_{af}(v) + (1 - \rho_f)\eta \gamma_1 P_{af}] \leq \bar{P}; \quad 2). \ P_{af}(v) \geq 0; \quad 3). \ 0 < \rho_f < 1.
\]

In problem \((P2)\), plugging Eq. (7) into the objective function, the equation \((b)\) holds. Equation \((c)\) is satisfied because the optimal solutions exists when \(A_3(v) = A_4(v). \ A_3(v)\) and \(A_4(v)\) are shown follow
\[
\begin{align*}
A_3(\mu) &= (1 + \rho \gamma_1 P_S(\mu))^{-\beta}; \\
A_4(\mu) &= (1 + (1 - \rho)\eta \gamma_1 P_S(\mu))^{-\beta}
\end{align*}
\]
(26)
Problem \((P2)\) is convex and thus the unique optimal solution can be obtained, which is similar to the analyses under half duplex mode. Here we omit the details.

### B. Optimal Resource Allocation Schemes Under Full Duplex Mode

We solve the EC maximization problem for wireless powered relay based IoT networks under full duplex mode. Then, the statistical QoS guarantees optimal access point power control policy, denoted by \(P_{af}^*(v)\), and the optimal power splitting ratio, denoted by \(\rho_f^*\), can be derived, which are shown in Theorem 2.

Theorem 2: For wireless powered relay based IoT networks with full duplex transmission, the statistical QoS provisioning optimal joint source node power control policy and power splitting ratio allocation scheme is given by
\[
P_{af}^*(v) = \begin{cases} 
1 & \text{if } \gamma \geq \gamma_{th2}; \\
\frac{1}{\gamma \eta + \zeta + \gamma \eta} & \text{if } \gamma < \gamma_{th2};
\end{cases}
\]
(27)
where \(\gamma_{th2}\) denotes the cutoff SNR threshold. This threshold can be numerically derived by substituting Eq. (27) into
\[
\int_{0}^{\infty} \int_{0}^{\infty} \left[ P_{af}^s + (1 - \rho_f^s)\eta \gamma_1 P_{af}^s \right] p_{\Gamma}(\gamma_1)p_{\Gamma}(\gamma_2)d\gamma_1d\gamma_2 = \bar{P}.
\]
(28)
Proof 2: We omit the proof details. Please refer to the proof of Theorem 1.

Observing the optimal resource allocation scheme in Theorem 2, we find that, for wireless powered relay based IoT networks, the optimal access point optimal power control policy is related to $\gamma_1$, $\gamma_2$, $\kappa$ and $\theta$, while the optimal power splitting ratio is the function of $\gamma_2$ and $\zeta$. To further analyze the insights of Theorems 1 and 2, we give some remarks which correspond to the very high/low R-to-I SNR conditions (i.e., remarks 1 and 2), the very high/low self-interference conditions (i.e., remarks 3 and 4), and the very stringent/loose QoS constraints (i.e., remarks 5 and 6), respectively, shown as follows.

Remark 1: Under the very high R-to-I SNR condition ($\gamma_2 \to \infty$), the optimal power splitting ratios for both half duplex mode ($\rho_{h}^*$) and full duplex mode ($\rho_{f}^*$) converge to 1.

Remark 2: Under the very low R-to-I SNR condition ($\gamma_2 \to 0$), the optimal power splitting ratios for both half duplex mode ($\rho_{h}^*$) and full duplex mode ($\rho_{f}^*$) approach to 0.

Remark 3: Under the very high self-interference condition ($\zeta \to 0$), for given $\gamma_2$ and $\eta$, optimal power splitting ratio for full duplex mode ($\rho_{f}^*$) converges to 1.

Remark 4: Under the very high self-interference condition ($\zeta \to 1$), for given $\gamma_2$ and $\eta$, optimal power splitting ratio for full duplex mode ($\rho_{f}^*$) is reduced to $\gamma_2\eta/(1 + \gamma_2\eta)$.

Remark 5: As the QoS requirement is very stringent ($\theta \to \infty$), the optimal access point power allocation for full duplex mode converges to

$$P_{af}^* = \frac{\sigma}{\gamma_1}, \quad (29)$$

where $\sigma = \lim_{\theta \to \infty} (\zeta \rho_f) - \frac{\eta}{\gamma_2} - (\zeta \rho_f)^{-1}$, which becomes the channel inversion scheme.

Remark 6: As the QoS requirement is very loose ($\theta \to 0$), the optimal access point power allocation for full duplex mode is

$$P_{af}^* = \frac{1}{\gamma_2(1 + (1 - \rho_f)\eta \gamma_1)} - \frac{1}{\zeta \rho_f \gamma_1}, \quad (30)$$

which is different from the water-filling power allocation scheme in statistical provisioning point-to-point wireless powered IoT networks [45].

Comparing Theorem 1 with Theorem 2, we find that when the relay node suffer from little self-interference ($\zeta = 1$), the optimal power splitting ratio under full duplex mode is equivalent to that under half duplex mode. When the relay node suffer serious self-interference ($\zeta \neq 0$), the optimal power splitting ratio under full duplex mode is larger than that under half duplex mode.

V. PERFORMANCE EVALUATION

In this section, we conduct the numerical simulations to evaluate the performance of our proposed statistical delay-bounded QoS guaranteed resource allocation schemes for wireless powered relay based IoT networks. Throughout the simulations, we set $B = 1$ MHz, $T_f = 0.2$ ms, $P = 10$ dB, $s = 0.5$, $\alpha = 4$, and $\eta = 0.6$, respectively [46]. First, to verify the statistical QoS aware characteristic, we plot the optimal access point power control policy versus the delay-bounded QoS requirement and instantaneous CSI under

![Figure 2](image-url)
different self-interference conditions in Fig. 2. Second, since the wireless powered relay is considered in this article, we depict the optimal power splitting ratio at relay node versus the self-interference parameter and R-to-I channel state information in Figs. 3 and 4, respectively. To further demonstrate the effective capacity improvement of our developed full duplex statistical QoS guaranteed optimal resource allocation scheme, we compare the optimal resource allocation under full duplex mode with the optimal resource allocation scheme under half duplex mode.

Figures 2(a), 2(b) and 2(c) depict the optimal access point transmit power versus the statistical QoS exponent and instantaneous CSI of A-to-R link under the self-interference parameter $\zeta = 0.01, \zeta = 0.1$ and $\zeta = 1$, respectively. In this simulation, we set the R-to-I SNR $\gamma_2 = 10$ dB. We can observing from Figs 2(a)- 2(c) that the investigated optimal access point power allocation scheme allocates more power to the links with loose QoS requirements and less power to the links with stringent QoS requirements. In Fig. 2(a) and 2(b), when QoS requirement is very loose ($\theta \to 0$), the developed optimal access point power allocation scheme allocates more power to the links with high instantaneous CSI of A-to-R link. Nevertheless, in Fig. 2(c), when QoS requirement is very loose ($\theta \to 0$), the developed optimal access point power allocation schemes allocate more power to the links with low instantaneous CSI of A-to-R link. This demonstrate the analysis in Remark 6, which indicates that when the delay-bounded QoS requirement is very loose, the optimal access point power control scheme is not the water-filling power allocation scheme.

Figure 3 draws the curves of optimal power splitting ratio under full duplex mode versus self-interference parameter $\zeta$ under different power conversion factor ($\eta = 0.4, 0.6, 0.8, 1.0$). Fig. 3 illustrates that the optimal power splitting ratio under full duplex decreases as self-interference parameter $\zeta$ increases. When $\zeta = 1$, the optimal power splitting ratio under full duplex mode is the same as the optimal power splitting ratio under half duplex mode. Fig. 3 illustrate that for wireless powered relay based IoT networks under full duplex mode, more power is used for information decoding than energy harvesting. We can also observe from Fig 3 that with the increase of power conversion factor, the optimal power splitting ratio increases.

Figure 4 plots the curves of optimal power splitting ratio for wireless powered relay based IoT networks under full duplex mode versus the instantaneous CSI of R-to-I link. We can observe from Fig. 4 that with the increase of instantaneous CSI of R-to-I link, the optimal power splitting ratio under full duplex mode increases. Besides, when the instantaneous CSI of R-to-I link approaches to infinity, the optimal splitting ratio...
under full duplex mode converges to 1, which demonstrate the analyses in Remarks 1 and 2. This is because if the R-to-I link has a better channel state, a larger proportion of energy will be applied for information decoding. We can also obtain from Fig. 4 that as the increase of self-interference cancellation coefficient, the optimal power splitting ratio under full duplex transmission mode decreases. This illustrates that if the wireless powered relay suffers from a more serious self-interference, a smaller proportion of energy will be used for information decoding.

Figure 5 compares the performance of our developed optimal resource allocation scheme for wireless powered relay based IoT networks under half duplex mode and full duplex mode, respectively. Fig. 5 illustrates that for wireless powered relay based IoT networks, employing full duplex mode can achieve the effective capacity improvement comparing with the half duplex mode. Besides, we can also obtain from Fig. 5 that when the self-interference cancellation coefficient varies from $10^{-5}$ to $10^{-1}$, the effective capacity for wireless powered relay based IoT networks decreases as the statistical QoS exponent increases.

VI. CONCLUSION

This article exploited the statistical QoS guaranteed joint optimal access point power allocation and power splitting ratio schemes for a wireless powered relay based IoT network. Half duplex mode and full duplex mode were considered in this article. We built the full duplex model by introducing a self-interference coefficient. We formulated the effective capacity maximization problems and derived the closed-form expressions of the optimal resource allocation schemes, under half duplex mode and full duplex mode, respectively. Extensive simulations were conducted to evaluate the performance of our investigated resource allocation schemes for wireless powered relay based IoT networks. The simulation results confirms the highlights of the proposed resource allocation schemes, which effectively guarantees the statistical delay-bound QoS.

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YONGPENG SHI (Member, IEEE) received the B.S. degree in electronic information science from Shaanxi Normal University, Xi’an, China, in 2001, and the M.S. and Ph.D. degrees in computer science from Xidian University, Xi’an, in 2008 and 2018, respectively. He has been working with Luoyang Normal University, since 2001. He has published more than ten peer-reviewed papers in many high quality publications, including prestigious IEEE journals and conferences. His research interests include the next generation wireless communications, space-air-ground integrated networks, cloud computing, SDN, and NFV.

YUYIE XIA received the B.S. degree in electronic engineering from Henan Normal University, Xinxiang, China, in 2001, the M.S. degree in communication and information systems from Harbin Engineering University, Harbin, China, in 2004, and the Ph.D. degree in communication and information systems from Xidian University, Xi’an, China, in 2014. Since 2004, he has been with Luoyang Normal University, Luoyang, China. His research interests include the next generation wireless communications, communication signal processing, and multiple user access technology.

HAO LIN ZHANG (Member, IEEE) received the B.S. and M.S. degrees from Northwestern Polytechnic University, Xi’an, China, in 1985 and 1988, respectively, and the Ph.D. degree from Xidian University, Xi’an, in 1991. In 1991, he joined the School of Telecommunications Engineering, Xidian University, where he is currently a Senior Professor and the Dean. He is also the Director of the Key Laboratory in Wireless Communications Technology, a Key Member of the State Key Laboratory of Integrated Services Networks, one of the state government specially compensated scientists and engineers, the Field Leader with the Telecommunications and Information Systems, Xidian University, and an Associate Director of the National 111 Project. He has published more than 150 papers in journals and conferences. His current research interests include key transmission technologies and standards on broadband wireless communications for 5G and 5G-beyond wireless access systems.

**Y. Gao (Member, IEEE)** received the M.S. degree in information and communications engineering from Central South University, Changsha, China, in 2010, and the Ph.D. degree in information and communications engineering from Xidian University, Xi’an, China, in 2018. She worked as a Visiting Postgraduate Student with the Institute of Computing Technology, Chinese Academy of Sciences, Beijing, China, from 2008 to 2010. She has been working with Luoyang Normal University, since 2010. Her research interests include 5G/6G wireless networks with an emphasis on statistical QoS provisioning, energy efficient wireless networks, wireless powered communications networks, the Internet-of-Things networks, and ultradense networks.