

Power Adaptation in Buffer-Aided Full-Duplex Relay Networks with Statistical CSI

Nikolaos Nomikos, *Member, IEEE*, Themistoklis Charalambous, *Member, IEEE*, Demosthenes Vouyioukas, *Member, IEEE*, Risto Wichman, *Member, IEEE*, and George K. Karagiannidis, *Fellow, IEEE*

Abstract—In networks with multiple wireless nodes and especially in fast changing environments, the continuous acquisition of Channel State Information (CSI) may become infeasible. In this paper, we study the relay selection problem for a cooperative network, where Full-Duplex (FD) relays are equipped with buffers and only statistical CSI is available at the transmitters (CSIT). For this setting, a novel relay selection algorithm is proposed, named HyQoS, relying only on statistical CSIT and performing power adaptation. HyQoS solves an optimization problem for selecting the optimal set of relays. We consider two optimization approaches: 1) minimization of the total power consumed in the network, and 2) maximization of the throughput per energy unit, while guaranteeing a specific Quality of Service (QoS), in terms of Successful Transmission Probability (STP). The power allocation problem is formulated as a nonlinear optimization one, taking into account inter-relay interference and residual loop interference. Numerical results show that HyQoS can reduce the power expenditure and increase the throughput, by using only statistical CSIT.

Index Terms—Full-duplex relaying; adaptive link selection; buffer-aided relays; power adaptation; statistical CSIT.

I. INTRODUCTION

Depending on the ability of the relay for simultaneous transmission and reception, Full-Duplex (FD) and Half-Duplex (HD) relaying provide a trade-off between spectral efficiency and interference avoidance. FD relays transmit and receive at the same time and on the same channel, thus achieving higher spectral efficiency. However, Loop Interference (LI) from the relay's output to the relay's input antenna results in performance degradation. In [1] and [2], LI mitigation techniques and practical issues on LI cancellation were considered.

For relays without buffers, a hybrid FD/HD scheme was proposed in [3], outperforming schemes based on either FD or HD relaying. Focusing on multi-user networks, [4] studied power adaptation with QoS guarantees, imposing rate and transmit power constraints. The proposed algorithms allow the efficient integration of FD relaying by mitigating LI and uplink/downlink interference. Recently, the authors of [5] investigated power and rate adaptation in FD relaying

with instantaneous CSIT. In the same work, various policies were developed, offering gains in spectral efficiency without requiring a large number of relays or full LI cancellation.

When relays are equipped with buffers, Buffer-Aided (BA) relaying offers increased flexibility in algorithmic design and improved performance [6]. In a HD network, max – link selection was proposed in [7] where in each time-slot, a BA relay is selected to receive or transmit, thus achieving a diversity gain twice the number of relays for large buffer size. Several works aim at FD operation through successive relaying [8]–[10], where the source and one relay transmit simultaneously. So, when multiple BA relays are available, Successive Opportunistic Relaying (SOR) can recover the spectral loss of HD relaying. In [11], a hybrid cooperation scheme with transmit power adaptation has been proposed, while for *single-relay* networks, Zlatanov *et al.* [12] showed that BA relaying improves the throughput of FD systems, due to improved robustness. The impact of statistical delay constraints on the achievable rate of a BA FD network was studied in [13]. It was concluded that when buffering at the source is possible, asymmetric delay constraints at the source and the relay can increase the data rate. Finally, the authors in [14] consider a single-relay network with a non-saturated source and FD/HD relaying. The problem that is closest to ours is [14, IV-A], where statistical CSIT is exploited, in order to maximize the packet arrival rate at the source under a power constraint. Nonetheless, in that work, exploiting statistical CSIT resulted only in FD relaying and the main goal was to maximize the end-to-end capacity.

In this paper, we consider a network with a saturated source, fixed-rate transmissions, multiple BA FD relays, statistical CSIT and instantaneous CSI at the receivers. For this network setup, we aim at: 1) minimizing the overall power consumption of the network at each *frame*, and 2) maximizing the throughput per energy unit of the network. Here, a frame is defined as a period of time consisting of several time-slots, for which the statistics of the channel remain unchanged and link selection and power allocation are performed under a desired STP condition. Towards this end, a hybrid FD/SOR/HD link selection algorithm, hereafter called HyQoS, is proposed, in which the relay selection process is done, at the start of each frame, via optimization problems. The effect of the buffer state of the relays on the performance of the system within a frame is taken into account in some of the optimization problems considered. It is shown that HyQoS can minimize the energy consumption or maximize the throughput depending on the optimization problem used.

N. Nomikos and D. Vouyioukas are with the Department of Information and Communication Systems Engineering, University of the Aegean, Samos, Greece. *Emails:* {nnomikos, dvouyiou}@aegean.gr.

T. Charalambous is with the Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Espoo, Finland. *Email:* themistoklis.charalambous@aalto.fi.

R. Wichman is with the Department of Signal Processing and Acoustics, School of Electrical Engineering, Aalto University, Espoo, Finland. *Email:* risto.wichman@aalto.fi.

G. K. Karagiannidis is with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece. *Email:* geokarag@auth.gr.

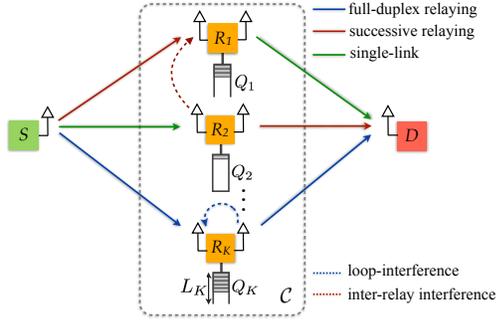


Fig. 1. System model.

II. SYSTEM MODEL AND PRELIMINARIES

Fig. 1 depicts a two-hop system with a single-antenna source S , a single-antenna destination D and a cluster \mathcal{C} of Decode-and-Forward (DF) relays. The relays are equipped with two antennas and are able to operate in FD mode. Each relay R_k holds a buffer (data queue) Q_k of length L_k where it can store source data that has been decoded and can be forwarded to the destination. The parameter $l_k \in \mathbb{Z}_+$, $l_k \in [0, L_k]$ denotes the number of data elements that are stored in buffer Q_k . For simplicity of exposition, we assume that $L_k = L, \forall k \in \{1, 2, \dots, K\}$.

A flat block fading Rayleigh channel and Additive White Gaussian Noise (AWGN) are assumed. Within a frame T , consisting of several time-slots, the fading coefficients $h_{ij}^{(T)}$ (for the $i \rightarrow j$ link) change from slot to slot; they are distributed according to a circularly symmetric complex Gaussian distribution with zero mean and variance $(\sigma_{ij}^{(T)})^2$, i.e., $h_{ij}^{(T)} \sim \mathcal{CN}(0, (\sigma_{ij}^{(T)})^2)$. The statistics of the channel change from frame to frame. Hereafter, we drop T , considering what happens within a single frame. The channel gains are $g_{ij} = |h_{ij}|^2$ and exponentially distributed. Also, the circularly symmetric complex Gaussian noise N has zero mean and variance σ_n^2 (i.e., $N \sim \mathcal{CN}(0, \sigma_n^2)$). Only statistical CSIT is available over a frame T , while at each time-slot, receivers are able to acquire full CSI. As relays support FD operation, LI degrades the network's performance. Due to imperfect LI cancellation, residual LI remains. $h_{R_k R_k}$ denotes the LI channel between the antennas of relay R_k , whose gain $g_{R_k R_k}$ is exponentially distributed, i.e., $h_{R_k R_k} \sim \mathcal{CN}(0, \sigma_{R_k R_k}^2)$; similar models are considered in [14]–[16]. The operation is divided in time-slots, where in each slot t a relay selection strategy among FD, SOR and HD is adopted. Regardless of the strategy, the source's transmit power is denoted by P_S and the relay's by P_{R_k} . Moreover, the system uses automatic repeat request (ARQ) terminated at the relays and the source.

The interference power at a receiving node k , denoted by I_k , includes the interference from all the concurrent transmitting nodes in the network, apart from the intended transmitter i and the thermal noise; it is given by $I_k(\mathbf{P}) \triangleq \sum_{j \neq i} g_{jk} P_j + \sigma_n^2$, where $\mathbf{P} = [P_1 \ P_2 \ \dots \ P_m]^T$ and m is the number of transmitting nodes. Therefore, the Signal-to-Interference-plus-Noise Ratio (SINR) at receiver k is given by $\Gamma_k(\mathbf{P}) = \frac{g_{ik} P_i}{\sum_{j \neq i} g_{jk} P_j + \sigma_n^2}$. From this expression it can be observed that the value of P_j will scale the interference level in the network.

The QoS is measured in terms of SINR. Hence, indepen-

dently of nodal distribution and traffic pattern, a transmission from a transmitter to its corresponding receiver is successful if the SINR of the receiver is greater or equal to the *capture ratio* γ_0 , i.e., $\Gamma_k(\mathbf{P}) \geq \gamma_0$; the value of γ_0 depends on the modulation and coding characteristics of the radio, such as, the required data rate of the application and the error-correction coding technique. An outage occurs at the k -th receiver when $\Gamma_k(\mathbf{P}) < \gamma_0$, and we denote this outage probability by $\mathbb{P}(\Gamma_k(\mathbf{P}) < \gamma_0)$. Hence, the instantaneous SNR from S to R_i and the instantaneous SINR from R_j to D when link-pair (R_i, R_j) is selected for FD (for FD relaying $i = j$) or SOR relaying, are expressed as

$$\frac{g_{S R_i} P_S}{g_{R_j R_i} P_{R_j} + \sigma_n^2} \geq \gamma_0, \quad (1a)$$

$$\frac{g_{R_j D} P_{R_j}}{\sigma_n^2} \geq \gamma_0. \quad (1b)$$

Here, only statistical CSIT is available at each frame and the target is to ensure that the STP over a link is greater than or equal to a pre-defined threshold q_{th} (that can be application- or condition-dependent), i.e., $\mathbb{P}(\Gamma_k(\mathbf{P}) \geq \gamma_0) \geq q_{th}$. When this condition cannot be satisfied by any relay-pair in successive transmission or any of the K relays in FD mode, HyQoS selects a single-link instead. To achieve increased diversity, max-link selection [7] is adopted, thus necessitating the use of buffering at the relays. In max-link, there is no interference between relays; so, in the case of a $\{S \rightarrow R\}$ link activation, (1a) has the same form as (1b).

If we consider algorithms that do not use power adaptation (i.e., they just fix their transmit power), then it would be difficult to efficiently share the total power between the source and the selected relay, and the powers $(P_S^*, P_{R_j}^*)$ are chosen *a priori*. $\mathbb{P}((1b))$ can be expressed easily, since $g_{R_j D}$ is exponentially distributed (i.e., $g_{R_j D} \sim \text{Exp}(\nu)$, $\nu > 0$). In addition, (1a) can be written as $g_{S R_i} P_S - g_{R_j R_i} \gamma_0 P_{R_j} \geq \gamma_0 \sigma_n^2$. This linear combination of exponentially distributed variables $g_{S R_i}$ and $g_{R_j R_i}$ can be shown to have the following distribution:

$$f_X(x) = \frac{\lambda \mu}{\lambda P_S + \mu \gamma_0 P_{R_j}} \begin{cases} \exp\left(-\frac{\mu}{P_S} x\right), & \text{if } x \geq 0, \\ \exp\left(\frac{\lambda}{\gamma_0 P_{R_j}} x\right), & \text{if } x < 0. \end{cases}$$

where $g_{S R_i} \sim \text{Exp}(\mu)$ and $g_{R_j R_i} \sim \text{Exp}(\lambda)$, $\lambda, \mu > 0$. Thus, statistical CSI knowledge allows for computing the optimal power levels, for the case the power is kept constant.

Let $F_W(w)$ denote the cumulative distribution function (cdf) of a random variable W ; e.g., for the exponential distribution $F_W(w) = 1 - \exp(-\lambda w)$. Then, $\mathbb{P}((1b))$ is given by

$$\mathbb{P}((1b)) = 1 - F_{g_{R_j D}}\left(\frac{\gamma_0 \sigma_n^2}{P_{R_j}}\right) = \exp\left(-\nu \frac{\gamma_0 \sigma_n^2}{P_{R_j}}\right). \quad (2a)$$

$\mathbb{P}((1a))$ is derived by

$$\begin{aligned} \mathbb{P}((1a)) &= 1 - F_{g_{S R_i} P_S - \gamma_0 g_{R_j R_i} P_{R_j}}(\gamma_0 \sigma_n^2) \\ &= \frac{P_S \lambda}{P_S \lambda + \gamma_0 P_{R_j} \mu} \exp\left(-\mu \frac{\gamma_0 \sigma_n^2}{P_S}\right). \end{aligned} \quad (2b)$$

Note that when there is no interference, the distribution should revert to an exponential distribution as for the $\{R \rightarrow D\}$ link; this corresponds to the case for which $\lambda \rightarrow \infty$. Hence,

$$\begin{aligned} \mathbb{P}((1a)) &= \lim_{\lambda \rightarrow \infty} \frac{P_S \lambda}{P_S \lambda + \gamma_0 P_{R_j} \mu} \exp\left(-\mu \frac{\gamma_0 \sigma_n^2}{P_S}\right) \\ &= \frac{P_S}{P_S} \exp\left(-\mu \frac{\gamma_0 \sigma_n^2}{P_S}\right) = \exp\left(-\mu \frac{\gamma_0 \sigma_n^2}{P_S}\right). \end{aligned} \quad (3)$$

III. THE HyQoS RELAY SELECTION ALGORITHM

HyQoS chooses a link-pair $\{S \rightarrow R_i, R_j \rightarrow D\}$ at the start of each frame, denoted by (R_i, R_j) , among *all the feasible link-pairs for FD or SOR relaying*, or, a single link if FD and SOR relaying is not feasible but HD is, such that a certain utility is maximized while at the same time aiming at using the minimum power required to guarantee the QoS requirements.

A. Power minimization scheme

Firstly, we focus on the case of a full-buffer model, i.e., buffers do not overflow or underflow and thus, a frame's throughput is not affected by the buffer status. The selected links retain the statistics for a frame, accounting for several time-slots. A QoS constraint on the STP q_{th} , that is given in terms of SINR, is chosen. When FD or SOR transmission fails, the activation of one link (from source to relay or relay to destination) is attempted, if q_{th} can be satisfied.

To minimize the total power consumption $P_S + P_{R_j}$ on a link-pair, while guaranteeing a QoS level q_{th} for the SINR, the following optimization problem is formulated:

$$\textbf{Problem 1:} \quad \min_{P_S, P_{R_j}} \{P_S + P_{R_j}\} \quad (4a)$$

$$\text{s.t.} \quad \min\left(\mathbb{P}((1b)), \mathbb{P}((1a))\right) \geq q_{th}, \quad (4b)$$

$$0 \leq P_i \leq P_{i,\max}, \quad i \in \{S, R_j\}. \quad (4c)$$

Objective (4a) minimizes the sum of power levels $P_S + P_{R_j}$. Note that coupling the power constraints in the network has been extensively used in the literature (see, for example, [14]) and it is associated with minimizing the total energy spent in the network. Problem (4) is *efficiently* solved, thus providing the optimal power levels P_S^* and $P_{R_j}^*$, as follows: first, $\mathbb{P}((1b))$ is decreasing with P_{R_j} , and therefore, condition (4b) can be decomposed into two inequalities: first, $\mathbb{P}((1b)) \geq q_{th}$, which always holds with equality and by which, P_{R_j} is determined; second, given P_{R_j} and q_{th} , a line search over P_S is performed on $\mathbb{P}((1a)) = q_{th}$. By (R_{i^*}, R_{j^*}) we denote the optimal link-pair (R_i, R_j) , i.e., the link-pair for which the minimum power expenditure is achieved; for FD relaying $i = j$.

Since we are considering BA relays, the number of packets in the buffer might affect the network's performance. For example, if a buffer is almost full, then it can accept a limited number of packets within a frame. Similarly, if a buffer is empty, it can transmit a limited number of packets. When FD relaying is selected, packets arrive and leave from the same buffer and due to the fixed rate, there is no possibility for buffer overflow and underflow. Based on these observations, it is evident that the optimization must consider the buffer

status. So, in every frame, suppose we have N time-slots (N is big enough). Since the STP is given by (2a) and (2b), the expected number of packets that are actually transmitted in frame k , for the $\{R \rightarrow D\}$ and $\{S \rightarrow R\}$ links are:

$$T_{\text{frame}, R_j D}[k] = \min\{Q_j[k], \mathbb{P}((1b))N\}, \quad (5a)$$

$$T_{\text{frame}, S R_j}[k] = \min\{L - Q_j[k], \mathbb{P}((1a))N\}. \quad (5b)$$

It can be observed that problem (4) does not take into account the queue size and the size might affect the number of time-slots there is a transmission. For this reason, we consider minimizing the *power expenditure per packet* instead, since the power spent per packet gives the efficiency with which the scheme works w.r.t. the energy spent. This can be found by computing the total power spent over the *average* number of packets transmitted. For the $\{R \rightarrow D\}$ link, this is given by

$$\begin{aligned} &\min\left\{\frac{P_{\text{frame}}}{Q_j[k]}, \frac{P_{R_j} N}{\mathbb{P}((1b))N}\right\} \\ &= \min\left\{\frac{\mathbb{E}(N_t) P_{R_j}}{Q_j[k]}, \frac{P_{R_j}}{\mathbb{P}((1b))}\right\} = \frac{P_{R_j}}{\mathbb{P}((1b))}, \end{aligned} \quad (6)$$

where $\mathbb{E}(N_t) = Q_j[k]/\mathbb{P}((1b))$ is the expected number of transmissions for emptying the buffer and P_{frame} is the power per frame. Similarly, for the $\{S \rightarrow R\}$ link, this is given by

$$\min\left\{\frac{P_{\text{frame}}}{L - Q_j[k]}, \frac{P_S N}{\mathbb{P}((1a))N}\right\} = \frac{P_S}{\mathbb{P}((1a))} \quad (7)$$

Hence, the optimization problem can be written as

$$\textbf{Problem 2:} \quad \min_{P_S, P_{R_j}} \left\{\frac{P_S}{\mathbb{P}((1a))} + \frac{P_{R_j}}{\mathbb{P}((1b))}\right\} \quad (8a)$$

$$\text{s.t.} \quad \min\left(\mathbb{P}((1b)), \mathbb{P}((1a))\right) \geq q_{th}, \quad (8b)$$

$$0 \leq P_i \leq P_{i,\max}, \quad i \in \{S, R_j\}. \quad (8c)$$

It can be deduced from (6) and (7) that the buffer size is eventually not incorporated into the optimization problem, thus rendering this optimization approach inappropriate for using buffer state information.

B. Throughput per energy unit maximization scheme

Another important metric that can be used by HyQoS is *throughput per energy unit*. Towards this end, power adaptation will provide the corresponding transmit power values. Thus, the optimization goal considers the sum of the ratio of the throughput of each link over the power that will be used by the transmitting node.

$$\textbf{Problem 3:} \quad \max_{P_S, P_{R_j}} \left\{\frac{\min\{L - Q_i[k], N\} \mathbb{P}((1a))}{P_S} + \frac{\min\{Q_j[k], N\} \mathbb{P}((1b))}{P_{R_j}}\right\} \quad (9a)$$

$$\text{s.t.} \quad \min\left(\mathbb{P}((1b)), \mathbb{P}((1a))\right) \geq q_{th}, \quad (9b)$$

$$0 \leq P_i \leq P_{i,\max}, \quad i \in \{S, R_j\}. \quad (9c)$$

Again, constraints (9b), (9c) involve the STP and the maximum transmit power of each node.

C. The HyQoS algorithm

The HyQoS algorithm for a single frame T , applying to all optimization problems (namely, 1, 2 and 3), is summarized in Algorithm 1:

Algorithm 1 The HyQoS algorithm

- 1: **input** $P_S^{max}, P_R^{max}, \gamma_0$, Problem number: $p \in \{1, 2, 3\}$
 - 2: **for** frame $T = 1 : m, m \in \mathbb{N}$, **do**
 - 3: **input** $(\sigma_{ij}^{(T)})^2$ for all $i \rightarrow j$ links; these give ν_T, μ_T, λ_T (distribution parameters at frame T)
 - 4: Optimization problem p is solved for all possible link-pairs (at the start of frame T) to derive the set of link-pairs (R_i, R_j) for which FD/SOR transmission is feasible and the corresponding power levels.
 - 5: **if** FD/SOR transmission is feasible **then**
 - 6: (R_{i^*}, R_{j^*}) is the optimal solution of p .
 - 7: **else**
 - 8: (1a) is replaced by (3) and problem p - modified for a single link - is solved for minimizing the power consumption of a single link for HD transmission.
 - 9: **if** HD transmission is feasible **then**
 - 10: The link with the smallest power is selected.
 - 11: **else**
 - 12: No transmission until the frame period is over.
 - 13: **end if**
 - 14: **end if**
 - 15: **end for**
-

IV. NUMERICAL RESULTS AND DISCUSSIONS

We evaluate HyQoS for the three optimization problems, assuming a rate $r_0 = 1$ Bit-Per-Channel-Use (BPCU) and a frame size $N = 1000$ time-slots. Results are given for a single frame and the comparisons include FD relaying with fixed and equal power allocation and HD max-link [7] with fixed power allocation. In the results, $K = 3$, the buffers of the relays at the start of the simulation are half-full, the average $\{S \rightarrow R\}$ channel gains are denoted as $\sigma_{SR_1}^2 = 1, \sigma_{SR_2}^2 = 0.7, \sigma_{SR_3}^2 = 0.8$ and the average $\{R \rightarrow D\}$ channel gains as $\sigma_{R_1D}^2 = 0.7, \sigma_{R_2D}^2 = 1, \sigma_{R_3D}^2 = 0.6$. Regarding interference, LI channels are identical for all the relays and equal to $\sigma_{RR}^2 = 0.1$, while Inter-Relay Interference (IRI) channels are considered reciprocal and denoted as $\sigma_{R_1R_2}^2 = 0.8, \sigma_{R_1R_3}^2 = 0.6$ and $\sigma_{R_2R_3}^2 = 0.7$. The noise level is equal to 1mW and several STP (q_{th}) values are imposed.

A. Power minimization

Below, the power levels are derived from problems 1 and 2, while the throughput is determined by the STP (q_{th}) and the transmission mode, as long as the power constraint can be satisfied. Fig. 2 depicts the impact of q_{th} on the throughput performance. When the power levels of (4) or (8) are used, the average throughput of each link coincides with the imposed q_{th} and the decision on whether or not to transmit depends on the long-term channel statistics. For low transmit power, HD transmission provides improved performance. Then, HyQoS follows the behavior of FD relaying with $P = P_{max}$ up until about 16dBm, with significantly reduced power consumption.

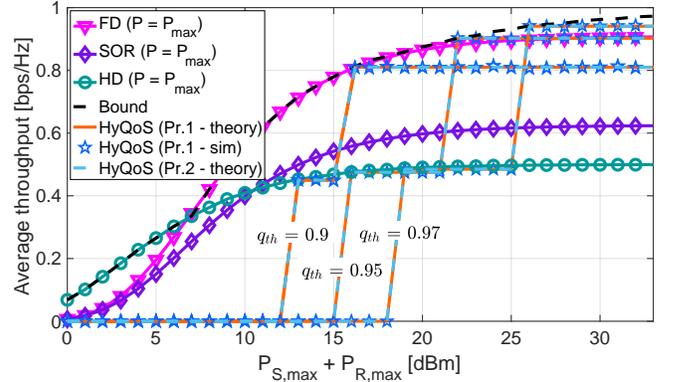


Fig. 2. Average throughput performance (problems 1–2) for various q_{th} .

TABLE I
POWER REDUCTION WHEN $P_S = P_R = 30dBm$

		q_{th}	0.75	0.85	0.95	0.985
Problem 1	$P_S + P_{R_j}$ (dBm)		10.03	13.04	20.03	28.93
	Reduction (%)		99.49	98.99	94.97	60.90
Problem 2	$P_S + P_{R_j}$ (dBm)		10.07	13.07	20.03	28.93
	Reduction (%)		99.48	98.98	94.96	60.89

In addition, the SOR curve is depicted when the best pair is selected (R_1 for reception and R_2 for transmission) with $P = P_{max}$ but, it is evident that, as IRI is stronger than LI, the performance is degraded. For higher power levels, HyQoS surpasses the performance of FD relaying with fixed power, thus achieving better performance. So, the importance of adapting q_{th} according to the available transmit power is demonstrated. Also, the curve of the maximum throughput values for each set of $P_{S,max}, P_{R,max}$ is included (bound).

Then, Table I includes the values of $P_S + P_{R_j}$ and the total power reduction for various q_{th} compared to the case when $P_S = P_{R_j} = 30dBm$. For higher q_{th} values, $P_S + P_{R_j}$ increases, however even for a value of 0.985, significant power reduction is achieved compared to using the maximum power levels. Thus, HyQoS provides power gains by exploiting channel statistics to set the power levels for a specific QoS target. Furthermore, it can be seen that similarly to the throughput results, the power levels deriving from both problems provide almost identical performance.

B. Throughput maximization

Next, the throughput performance of problem 3 is investigated. For the results in Fig. 3, it is assumed that the capacity of the buffers is larger than $N/2$ and thus, the performance of HD transmission is not affected by L . It is obvious that both HD and FD transmission modes are used, depending on the available transmit power. For lower transmit power values, HyQoS employs max-link selection, while for higher transmit power values FD relaying is performed. More importantly, here, the throughput is significantly increased, independently of the STP. For example, the case where $q_{th} = 0.75$ experiences improved throughput after 10 dBm when compared to the previous scenario. Also, as the transmit power increases,

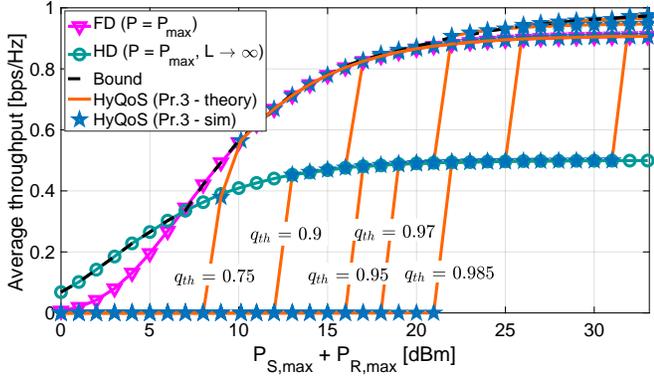


Fig. 3. Average throughput performance (problem 3) for various q_{th} .

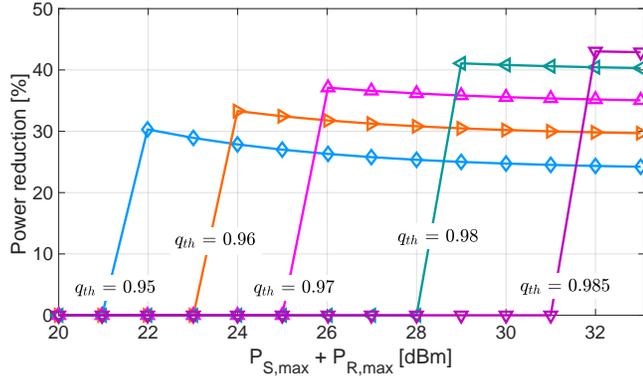


Fig. 4. Power reduction performance (problem 3) for various q_{th} , compared to the case of equal power allocation.

HyQoS is able to achieve the performance bound and surpass the equal power allocation of FD relaying.

In addition, Fig. 4 depicts the power reduction performance due to the optimal power allocation for FD transmission, deriving from problem 3. As a basis, the case of equal power allocation using maximum transmit power at the source and the relay is used. It is obvious that for increasing q_{th} values, power reduction improves. As more strict STP constraints are imposed, the power values are adjusted to reduce the LI of the FD relay and thus, lower power levels are adopted. From Fig. 3 and Fig. 4, it can be concluded that using the power levels from the solution of problem 3, allows HyQoS to provide improved throughput with lower power expenditure.

Finally, Fig. 5 illustrates the throughput performance of HyQoS with $q_{th} = 0.9$ and varying buffer size L . It can be observed that the HD transmission experiences reduced performance for smaller L . However, for increasing L , throughput improves, since the increased buffer capacity allows more packets to be transmitted in the network. On the contrary, for FD relaying, the buffer size does not affect the throughput performance, as the transmitted data are forwarded towards the destination without being stored in the buffer.

V. CONCLUSIONS

A hybrid BA relay selection algorithm was presented, aiming to provide a certain QoS level, in terms of STP under three optimization problems, by exploiting only statistical CSIT. The relay selection and the power levels are derived when either

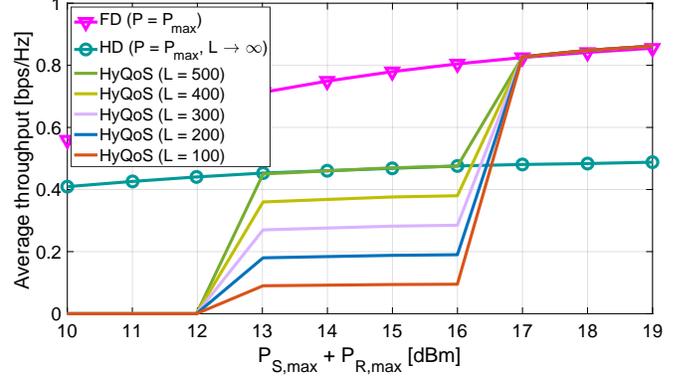


Fig. 5. Average throughput performance (problem 3) for various L .

power expenditure or throughput per energy unit are optimized. Performance evaluation showed that HyQoS improves the network's performance, requiring only a minimum amount of CSI for power adaptation.

REFERENCES

- [1] Z. Zhang, K. Long, A. V. Vasilakos and L. Hanzo, "Full-duplex wireless communications: Challenges, solutions, and future research directions," *Proc. of the IEEE*, vol. 104, no. 7, pp. 1369–1409, July 2016.
- [2] A. Sabharwal *et al.*, "In-band full-duplex wireless: Challenges and opportunities," *IEEE J. on Sel. Areas in Commun.*, vol. 32, no. 9, pp. 1637–1652, Sept. 2014.
- [3] T. Riihonen, S. Werner and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3074–3085, Sep. 2011.
- [4] X. Huang, K. Yang, F. Wu and S. Leng, "Power control for full-duplex relay-enhanced cellular networks with QoS guarantees," *IEEE Access*, vol. 5, pp. 4859–4869, 2017.
- [5] P. C. Sofotasios *et al.*, "Relay selection based full-duplex cooperative systems under adaptive transmission," *IEEE Wireless Commun. Lett.*, vol. 6, no. 5, pp. 602–605, Oct. 2017.
- [6] N. Nomikos *et al.*, "A survey on buffer-aided relay selection," *IEEE Commun. S. & T.*, vol. 18, no. 2, pp. 1073–1097, Secondquarter 2016.
- [7] I. Krikidis, T. Charalambous and J. S. Thompson, "Buffer-aided relay selection for cooperative diversity systems without delay constraints," *IEEE Trans. Wireless Commun.*, vol. 11, pp. 1957–1967, May 2012.
- [8] A. Ikhlef, J. Kim, and R. Schober, "Mimicking full-duplex relaying using half-duplex relays with buffers," *IEEE Trans. Vehicular Tech.*, vol. 61, no. 7, pp. 3025–3037, Sept. 2012.
- [9] N. Nomikos *et al.*, "A buffer-aided successive opportunistic relay selection scheme with power adaptation and inter-relay interference cancellation for cooperative diversity systems," *IEEE Trans. on Commun.*, vol. 63, no. 5, pp. 1623–1634, May 2015.
- [10] R. Simoni *et al.*, "Buffer-aided diamond relay network with block fading and inter-relay interference," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7357–7372, Nov. 2016.
- [11] N. Nomikos *et al.*, "Hybrid cooperation through full-duplex opportunistic relaying and max-link relay selection with transmit power adaptation," *IEEE Int. Conf. on Commun. (ICC)*, pp. 5706–5711, 2014.
- [12] N. Zlatanov, D. Hranilovic and J. S. Evans, "Buffer-aided relaying improves throughput of full-duplex relay networks with fixed-rate transmissions," *IEEE Commun. Lett.*, vol. 20, no. 12, pp. 2446–2449, Dec. 2016.
- [13] D. Qiao and M. C. Gursoy, "Statistical delay tradeoffs in buffer-aided two-hop wireless communication systems," *IEEE Trans. on Commun.*, vol. 64, no. 11, pp. 4563–4577, Nov. 2016.
- [14] K. T. Phan and T. Le-Ngoc, "Power allocation for buffer-aided full-duplex relaying with imperfect self-interference cancellation and statistical delay constraint," *IEEE Access*, vol. 4, no. , pp. 3961–3974, 2016.
- [15] L. J. Rodriguez, N. H. Tran and T. Le-Ngoc, "Optimal power allocation and capacity of full-duplex AF relaying under residual self-interference," *IEEE Wireless Commun. Lett.*, vol. 3, no. 2, pp. 233–236, April 2014.
- [16] L. Chen, S. Han, W. Meng and C. Li, "Optimal power allocation for dual-hop full-duplex decode-and-forward relay," *IEEE Commun. Lett.*, vol. 19, no. 3, pp. 471–474, March 2015.