Optimal Power Control for Full Duplex Wireless Networks with Full Interference

Kudret Akcapinar
Department of Electronics Engineering
Sabanci University
Istanbul, TURKEY
Email: kudret@sabanciuniv.edu

Ozgur Gurbuz
Department of Electronics Engineering
Sabanci University
Istanbul, TURKEY
Email: ogurbuz@sabanciuniv.edu

Tonguc Unluyurt
Department of Industrial Engineering
Sabanci University
Istanbul, TURKEY
Email: tonguc@sabanciuniv.edu

***Abstract*—In this paper, an optimal power control scheme is proposed for applying in-band full-duplex (FD) communication in multi hop wireless networks subject to full interference, such as home wireless mesh networks. Considering both the self-interference due to FD operation and the inter node interference from all nodes, an optimization problem is formulated for maximizing the end-to-end throughput, and a linear programming based solution is developed for obtaining the optimal power allocations. Via detailed numerical experiments, it is shown that our solution outperforms a prominent FD multi hop scheme in the literature, where power control is based on single hop interference only. Furthermore, it is shown that FD multi hop with proposed optimal power control can triple the end-to-end throughput of a traditional HD multi hop network for low power, short range systems, and 80% improvement can be achieved for higher power. A hybrid FD-HD multi hop scheme is also proposed for cases when FD cannot be enabled on all nodes, and it is shown that the throughput of HD can be doubled with the hybrid scheme for moderate size networks.**

***Keywords*—Full duplex wireless, multi hop communication, relaying, self-interference.**

I. Introduction

A long-held taboo in wireless communication was that a radio cannot transmit and receive at the same time and on the same frequency band, due to the high self-interference (SI) observed at the receiver [1]. Recently, in the radio designs by applying passive (antenna level) and active (analog and digital) interference cancellation techniques, full duplex communication has been demonstrated and it is shown that, the spectral efficiency of traditional half-duplex (HD) systems can actually be doubled, without wasting any time or frequency resources [2], [3], [4]. As summarized in [5], the main challenge in FD communication is SI cancellation, and FD is more suitable for low power, short range systems, such as small cells and WiFi.

The architectural progression towards densification in 5G networks indicate that small cells and WiFi systems will become more widespread, they will be complemented with multi hop mesh structures, and FD is considered as one of the plausible alternatives for enhancing their capacity [6]. Promising results on FD wireless communications have motivated research on FD networking. [7] considers scheduling of multiple flows over known routes for investigating the end-to-end throughput performance of FD in multi hop wireless networks. It is shown that the end-to-end session throughput in an FD network can exceed twice of that of HD, due to much larger design space offered by FD. In [8], FD and HD are compared in multi hop large scale networks, considering a stochastic geometry model for the network topology. It is shown that the capacity gain of FD over HD is limited due to severe aggregate interference, and SI cancellation alone cannot ensure scalable FD wireless networking, emphasizing the need for power control. In [9], joint power allocation and routing is investigated for FD multi hop relaying under Nakagami-m fading channel. Assuming inter hop interference is cancelled via Markov Block Coding/Sliding Window Decoding (MBC/SWD), the power optimization is defined as the minimization of the weighted power sum of FD relay nodes, while the end-to-end link outage probability is kept below a threshold. In [10], an optimal power allocation solution is obtained, maximizing the end-to-end throughput of an FD multi hop network, assuming that the inter-node interference is limited to only one hop neighbors. It is shown that in order to maximize the end-to-end throughput, all the link rates should be equal, and at least one of the nodes should transmit at its maximum power. This solution, when applied into networks subject to full interference, is shown to approach the optimal solution with a constant gap as the network size increases. In [11], a medium access control (MAC) scheme with power control is proposed for a three node (two hop) FD WiFi network scenario, where the power control solution is found by a heuristic search based on equalized link quality and rates.

Full interference is a major problem in practical small cells, WiFi and mesh networks. For home networks, for instance, although wireless mesh networking can improve the access rates of nodes in far away rooms, behind many walls or floors, due to full interference, this improvement is limited: Since all the nodes hear each other, the channel is shared while forwarding packets over multiple hops, and the observed end-to-end rate of the far away node remains much lower than Gbps provided to the home, starving the bandwidth hungry applications, such as video streaming, gaming etc.

In this paper, we propose a linear programming based optimal power allocation scheme for FD multi hop wireless networks, which are subject to full interference. While maximizing the end-to-end throughput, the full interference assumption in our problem formulation makes our solution not only more realistic, but also different from the existing works on FD networks: In [9] the inter node interference is assumed to be totally cancelled via (MBC/SWD), and [10] considers only the interference from one hop neighbors for the calculation of the optimal power levels. [11] considers full interference for the special case of two hops (three nodes) only, proposing a heuristic power control solution, while our optimal power allocation solution applies to a multi hop FD network of any size. Our numerical performance analysis results indicate that FD multi hop with proposed optimal power control can improve the end-to-end throughput of a traditional HD multi hop network by a factor of almost three for low power, short range systems, and by 80% for higher power systems. Our scheme is also compared to the FD multi hop scheme in [10], and it is shown that the end-to-end throughput can be improved by the proposed FD power control, by up to a factor of two, depending on the system settings. We also propose a hybrid FD-HD approach, where FD is employed together with power control only on some of the nodes, and we show that significant improvements over traditional HD can still be achieved, doubling the throughput for moderate size networks. With the proposed optimal power allocation, FD promises a good potential for home wireless mesh networks, especially for bandwidth hungry applications, such as video streaming, gaming etc., since interference is fully considered and controlled across the entire multi hop network.

The rest of the paper is organized as follows: In Section II, the FD multi hop system model is presented, the end-to-end throughput under full interference is obtained and the power allocation problem is defined. In Section III, the optimization problem is formulated and a linear programming based solution method is devised for obtaining optimal power allocations. Section IV involves our performance analysis for FD with proposed power control and Section V presents our conclusions.

II. System Model

We consider a linear network of N nodes, where a source node wishes to deliver a single data stream to a destination node through multiple relay nodes, as depicted in Figure 1. All nodes are FD capable with a single antenna FD radio [4], so that they can simultaneously transmit and receive data on the same frequency band. A single flow is considered, so the source node (labeled as node 1) performs only transmission and the destination node (labeled as node N) performs only reception.

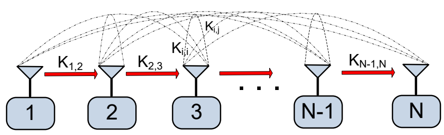


Figure 1: FD multihop communication system model in a linear network

The path of the data flow is assumed to be pre-determined, so that node i receives from node $(i-1)$ and transmits to node $(i+1)$, and due to FD capability, transmissions and receptions of each node are concurrent. Considering continuous data streaming, each node has data to send while receiving from the previous node. Also, it is assumed that all transmissions are synchronized, and the delays for decoding and forwarding is ignored.

Practically, FD communication is imperfect, since SI cannot be cancelled compeletely at the FD relay nodes. The effect of residual SI is modeled as the transmit power level attenuated by a constant factor, β, as presented for the single antenna FD radio in [4]. The channel gain between any two nodes i and j is denoted by $K_{i,j}$.

Letting an arbitrary node i, $(i \in \{1,\ldots,N-1\})$ has a maximum transmission power, denoted by $P_{i\,max}$ and defining the transmission power level of node i as $P_i \leq P_{i\,max}$, the Signal-to-Interference Ratio (SINR) observed at relay node i is calculated as:

$$SINR_i = \frac{K_{i-1,i}P_{i-1}}{\sigma^2 + \beta P_i + \sum\limits_{\substack{j=1 \\ j\notin\{i,i-1\}}}^{N-1} K_{j,i}P_j}. \tag{1}$$

In this expression, the numerator reflects the fact that data is received from node $(i-1)$, and the denominator reflects the full interference conditions, including the residual SI and the total inter node interference, as shown in the second and third terms. Note that multi packet reception is not possible, hence a node i receives from node $(i-1)$ only, and the transmissions of all other nodes are observed as inter node interference to node i. It is assumed that all nodes are subject to additive white gaussian noise with same power, σ^2, as shown in the first term in the denominator of (1). Also, same type of FD radio is assumed for all nodes, so the same SI suppression factor, β is assumed for all nodes.

At this point, for the brevity of the rest of the analysis and formulation of the optimization problem, we rename the SI suppression factor, β as $K_{i,i}$, so that the SI and inter node interference terms in (1) can be collected under one summation. (Although the two types of interference are of different nature, in both cases a multiplicative gain is represented, and the different indices make sure their values are different.) With this simplification, the achievable rate observed at a relay node i received from the transmission of node $(i-1)$, can be written as:

$$R_{i-1,i} = \log\left(1 + \frac{K_{i-1,i}P_{i-1}}{\sigma^2 + \sum\limits_{\substack{j=1 \\ j\neq i-1}}^{N-1} K_{j,i}P_j}\right). \tag{2}$$

The end-to-end throughput of the linear network is determined by the rate of the bottleneck link, defined as $\min\left\{R_{1,2}, R_{2,3}, \ldots, R_{N-1,N}\right\}$. Our goal in this paper is to obtain the optimal power allocations, i.e., P_i values, to maximize the end-to-end throughput.

Increasing the transmit power level of a node enhances the power of the intended signal at the next node on the path, however the residual SI as well as inter node interference to other nodes are also increased, degrading the link SINRs, affecting the end-to-end rate. We address this trade off by optimal power allocation by a linear programming based solution method provided in the next section.

III. Optimal Power Allocation

The end-to-end throughput of the linear network in Figure 1 can be maximized by solving for the optimal power levels in the following optimization problem:

$$\begin{aligned} z^* = &\max_{P_i} \min_{i\in\{2,3,\dots,N\}} \{R_{i-1,i}\} \\ &\text{s.t.} \\ &\quad 0 \le P_i \le P_{max}, \forall i \in \{1,\dots,N-1\}. \end{aligned} \tag{3}$$

Letting $z = \min_{i\in\{2,3,\dots,N\}}\{R_{i-1,i}\}$, we can consider the following Problem k, with $k = \{2,3,\dots,N\}$, where the minimum occurs at link $(k-1,k)$:

$$\begin{aligned} z_k^* = &\max z \\ &\text{s.t.} \\ &\quad z \le R_{i-1,i}, \forall i \in \{2,\dots,N\} - \{k\} \\ &\quad z = R_{k-1,k} \\ &\quad 0 \le P_i \le P_{max}, \forall i \in \{1,\dots,N-1\}. \end{aligned} \tag{4}$$

Then, z^* can be computed as $\max\{z_1^*, z_2^*, \dots, z_{N-1}^*\}$. The Problem k has non-linear constraints. Yet, for a fixed z, one can determine if $z_k^* \ge z$, by checking whether the linear programming model defined in (5) has a feasible solution as explained below.

By the substituting the rate expression from equation (2) into the first two constraints of (4), the constraints of Problem k can be rewritten as:

$$\begin{aligned} &(2^z - 1)\left(\sum_{\substack{j=1\\ j\neq i-1}}^{N-1} K_{j,i}P_j\right) - K_{i-1,i}P_{i-1} \le (1-2^z)\sigma^2 \\ &\qquad\qquad\qquad \forall i \in \{2,\dots,N\} - \{k\} \\ &(2^z - 1)\left(\sum_{\substack{j=1\\ j\neq k-1}}^{N-1} K_{j,k}P_j\right) - K_{k-1,k}P_{k-1} = (1-2^z)\sigma^2 \\ &\qquad 0 \le P_i \le P_{max}, i \in \{1,2,\dots,N-1\} \end{aligned} \tag{5}$$

For a fixed z, all the inequalities in (5) are linear and $z_k^* \ge z$ if there exists a power allocation vector P_i, $i \in \{1,2,\dots,N-1\}$ satisfying (5), which can be checked by any linear programming solver. Then, it is possible to find the optimal value for Problem k for $k = 1,\dots,N-1$ by conducting a search over the possible objective function values.

For the search procedure, we set the limits of the search interval as, $z \in [0,u]$, where u is defined as:

$$u = \min\left\{\log\left(1+\frac{P_{max}K_{1,2}}{\sigma^2}\right),\dots,\log\left(1+\frac{P_{max}K_{N-1,N}}{\sigma^2}\right)\right\}.$$

The search starts by setting z equal to the middle of the initial interval, and then the constraints are checked for feasibility by employing linear programming tools. If there are feasible power levels satisfying the constraints, the lower limit of the interval is updated as z; otherwise the upper limit of the interval is set to z, and the middle of the new interval is checked for feasibility. This process is continued until the length of search interval drops below a certain ϵ.

Note that, the optimal power allocations are for a given set of values, $K_{i,j}$, of the channel gain, which are assumed as provided or estimated as channel state information (CSI). When the channel gains change in time, the new CSI, which can be obtained and communicated by a MAC scheme, such as [11], which operates in accordance with the channel coherence time, and the new CSI can be used in finding the new optimal power allocations as proposed in this paper.

IV. Simulation Results

In this section, we present the end-to-end throughput performance of multi hop FD relaying with proposed optimal power allocation under a full interference scenario, in comparison to the following schemes: 1) multi hop FD relaying with power control which considers only single hop interference, as proposed in [10], 2) multi hop HD relaying, which assumes time division multi access (TDMA) for the transmissions of HD relay nodes[1] 3) multi hop hybrid HD and FD relaying with proposed power control for FD nodes and 4) single hop direct transmission. In the hybrid scheme, the network consists of a mixture of HD and FD nodes as in [12], but differently, we propose to place the FD nodes in between two HD nodes, forming subnetworks of three nodes. In each subnetwork, the proposed power allocation is employed for the transmissions of the first and the middle node (FD relay) as data is forwarded to the third node. Data is relayed over the subnetworks via TDMA, since all the end (first and third) nodes of the subnetworks are HD.

In the simulations, a path loss dominated channel model is assumed, and the channel gains are determined based on the generalized path loss model, $K_{i,j} = d_{i,j}^{-\alpha}$, where $d_{i,j}$ is the distance between nodes i and j, similar to the experiments in [10]. The system parameters are set as follows (unless varied as specified in an experiment scenario): The maximum transmission power per node is set as, P_{max} = 0 dBm, the separation between the source and destination nodes is 250m, the SI suppression factor is $\beta = K_{i,i}$ = -80 dB, the path loss exponent is taken as α = 4 and the noise power is set as σ^2 =-70 dBm.

[1]Note that each HD node can either transmit or receive at a time, and the transmissions need to be coordinated, since all nodes hear each other due to full interference conditions.

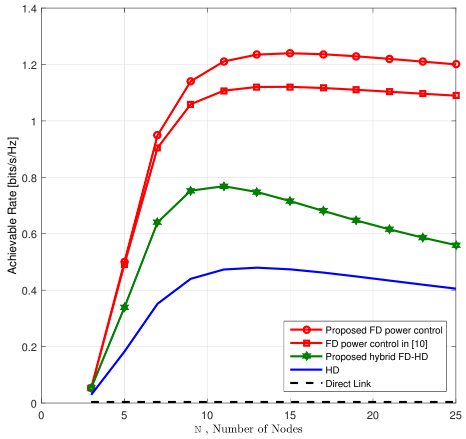


Figure 2: End-to-end throughput with respect to network size, P_{max} = 0 dBm, α = 4, $\beta = -80dB$

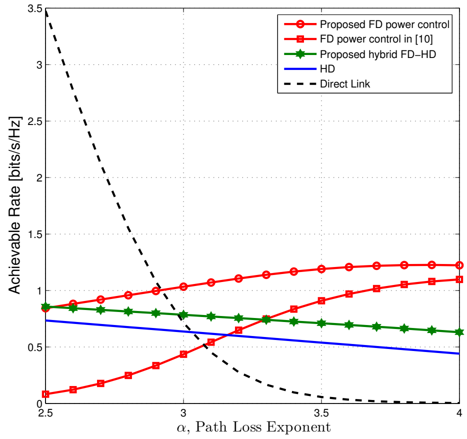


Figure 3: End-to-end throughput with respect to path loss exponent α, P_{max} = 0 dBm, N = 20, β = -80dB

Figure 2 shows the end-to-end throughput with respect to the network size, i.e. the number of nodes in the network. Clearly, multi hop communication enhances the end-to-end throughput as compared to direct transmission, and FD multi hop scheme with proposed optimal power control considering full interference provides the highest throughput, which is up to three times that of HD multi hop, also outperforming the algorithm in [10], where power control takes into account the interference effect of only single hop neighbors. The hybrid scheme performs below FD multi hop with optimal power control, but it still provides up to twice the throughput of HD multi hop. In Figure 3, we investigate the effect of the path loss exponent, α on the throughput, considering a network of 20 nodes. Figure 3 indicates that, multi hop communication can be preferred over direct transmission for α values larger than 3, which represent outdoor scenarios. FD with proposed optimal power control again outperforms all other schemes, the extent of which depends on the path loss. The hybrid FD-HD multi hop scheme is always more favorable over HD multi hop, and this scheme outperforms [10] for lower α values.

In the next experiment, we investigate the effect of the power budget, i.e., the maximum transmission power per node, P_{max}, on the throughput performance of a multi hop network of 20 nodes. As depicted in Figure 4, FD multi hop employing our power allocation offers the highest throughput for all power levels. More specifically, with higher power budget (P_{max}), the proposed FD multi hop scheme can almost double the performance of HD multi hop [10], and for lower power budget the gain over HD multi hop is improved up to three. For all schemes except [10], the throughput keeps increasing with increasing P_{max}. However, for [10], the end-to-end data rate starts to decrease after a certain P_{max}, approaching the performance of the hybrid FD-HD scheme. This is because, increasing P_{max} introduces higher inter node interference, and [10] only considers the interference of one hop neighbors in the calculation of power levels. Thanks to our optimal power allocation which considers full interference, i.e., inter

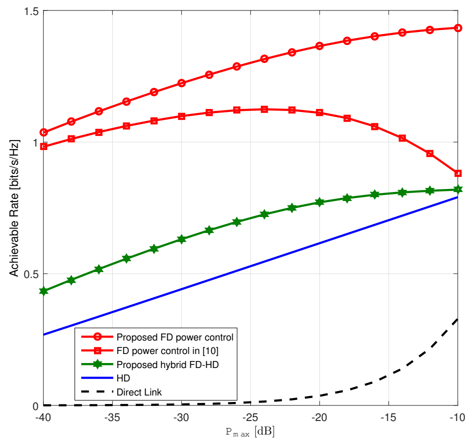
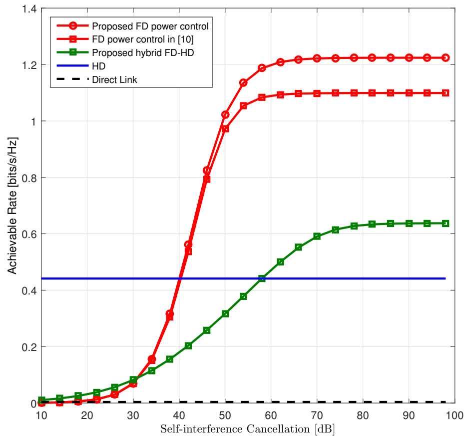


Figure 4: End-to-end throughput with respect to P_{max}, N = 20, α = 4, β = -80 dB

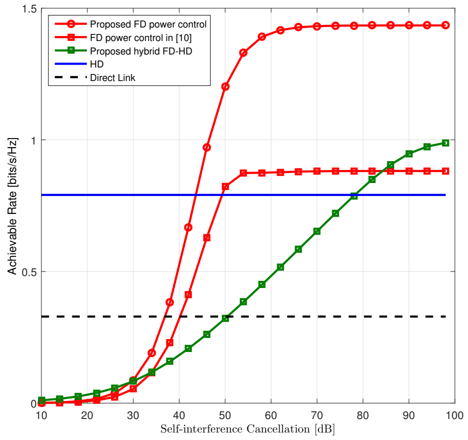
node interference from all nodes, the end to end throughput never decreases with increasing P_{max} for proposed FD power control. Lastly, it can be seen that the hybrid FD-HD improves the performance of HD, more for low power budget case.

In Figure 5, the end-to-end throughput is plotted as a function of the amount or level of SI suppression, measured as $|\beta|$ (in dB), considering low and high power budget (P_{max}) cases. It can be seen that, the performance of all FD schemes ameliorate with stronger SI suppression. However, the achievable rate does not change after a certain level of SI. In Figure 5 (a), it is depicted that proposed FD multi hop almost triples the performance of HD, while in Figure 5 (b), proposed FD achieves about 80% improvement over HD. Note also that, again FD multi hop with proposed optimal power allocation outperforms the FD solution suggested in [10] with a higher improvement for higher power budget, due to the correction in power control since full interference is considered.

It is worthwhile to note that, in all our experiments we have observed that the end-to-end throughput of FD multi hop is maximized when the rate of the all links in the network are



(a)



(b)

Figure 5: End-to-end throughput with respect to SI suppresion level, $|\beta|$, $N = 20$, $\alpha = 4$ (a) $P_{max} = 0$ dBm (Low power budget) (b) $P_{max} = 20$ dBm (High power budget)

equal. This is consistent with the work that considers FD multi hop with simplified single hop inteference [10], and the results of earlier works on two hop relaying, such as [13], [14], where it is shown that Nash equilibrium is reached when the link rates are equal. We have also verified that, for the case of three nodes (two hops), our power allocation solution is consistent with that of [11], which is a (heuristic) solution only for this special case, while we propose an optimal power allocation solution for a general size multi hop FD network under full interference.

V. Conclusions

We have proposed a linear programming based solution for optimal power allocation of FD nodes in multi hop wireless networks under full interference. Our numerical experiments show that, even with the moderate SI suppression, FD multi hop with optimal power allocation performs significantly better than HD multi hop relaying. More specifically, the HD throughput is tripled for low power systems, while for systems with high power budget, 80% throughput improvement over HD is observed. We also propose a hybrid FD-HD multi hop scheme with the same power control, and we show that significant enhancements over HD can be obtained, even when FD can be enabled on some of the nodes. Our results in this paper reveal the potential and performance upper bound for applying FD over multi hop networks that suffer from full interference, such as home wireless mesh networks, where the broadband rates are not leveraged and streaming type applications are striving to meet their bandwidth demand.

VI. Acknowledgement

This work was supported in part by TUBITAK Grant No: 113E222.

References

[1] A. Goldsmith, *Wireless Communications*. New York, NY, USA: Cambridge University Press, 2005.

[2] M. Duarte and A. Sabharwal, "Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results," in *Proceedings of the 44th Asilomar Conference on Signals, Systems and Computers (ASILOMAR)*, Nov 2010, pp. 1558–1562.

[3] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proceedings of the Sixteenth Annual International Conference on Mobile Computing and Networking*. New York, NY, USA: ACM, 2010, pp. 1–12.

[4] E. M. D. Bharadia and S. Katti, "Full duplex radios," in *Proceedings of the 13th ACM SIGCOMM Conference*, vol. 43. New York, NY, USA: ACM, 2013, pp. 375–386.

[5] A. Sabharwal, P. Schniter, D. Guo, D. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 9, pp. 1637–1652, Sept 2014.

[6] J. Andrews, S. Buzzi, W. Choi, S. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5g be?" *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065 – 1082, 2014.

[7] X. Qin, H. Zeng, X. Yuan, B. Jalaian, Y. T. Hou, W. Lou, and S. F. Midkiff, "Impact of full duplex scheduling on end-to-end throughput in multi-hop wireless networks," *IEEE Transactions on Mobile Computing*, vol. 16, no. 1, pp. 158–171, Jan 2017.

[8] X. Wang, H. Huang, and T. Hwang, "On the capacity gain from full duplex communications in a large scale wireless network," *IEEE Transactions on Mobile Computing*, vol. 15, no. 9, pp. 2290–2303, Sept 2016.

[9] B. Mahboobi and M. Ardebilipour, "Joint power allocation and routing in full-duplex relay network: An outage probability approach," *IEEE Communications Letters*, vol. 17, no. 8, pp. 1497 – 1500, July 2015.

[10] D. Ramirez and B. Aazhang, "Optimal routing and power allocation for wireless networks with imperfect full-duplex nodes," *IEEE Transactions on Wireless Communications*, vol. 12, no. 9, pp. 4692–4704, September 2013.

[11] H. L. W. Choi and A. Sabharwal, "Power-controlled medium access control protocol for full-duplex wifi networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 7, pp. 3601–3613, 2015.

[12] A. Sadeghi, S. Mosavat-Jahromi, F. Lahouti, and M. Zorzi, "Multi-hop wireless transmission with half duplex and imperfect full duplex relays," in *7th International Symposium on Telecommunications (IST)*, Sept 2014, pp. 1026–1029.

[13] Y. Shi, J. Wang, K. Letaief, and R. Mallik, "A game-theoretic approach for distributed power control in interference relay channels," *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 3151–3161, June 2009.

[14] T. Riihonen, S. Werner, and R. Wichman, "Transmit power optimization for multiantenna decode-and-forward relays with loopback self-interference from full-duplex operation," in *Proceedings of the 45th Asilomar Conference on Signals, Systems and Computers (ASILOMAR)*, Nov 2011, pp. 1408–1412.