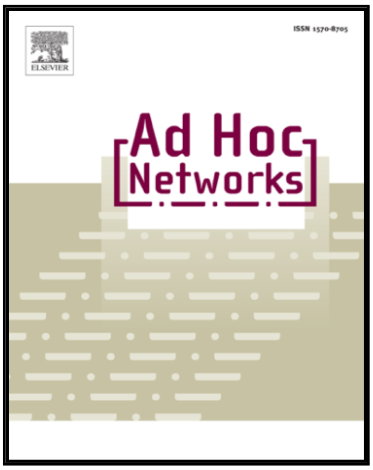

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Power Allocation and Routing for Full-duplex Multi Hop Wireless Networks under Full Interference

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Abstract

When traditional half-duplex (HD) radios are employed in indoor wireless mesh networks, such as home networks, interference among mesh nodes is a major impairment, as the end-to-end throughput is to be shared between all transmitting nodes. Full-duplex (FD) relaying can improve the end-to-end throughput, as simultaneous transmissions and receptions, hence simultaneous links are enabled, but FD nodes are subject to self-interference(SI) in addition to inter-node interference, resulting in a more complicated, full interference scenario. In this work, a power allocation solution is proposed along with routing for enabling FD in such multi hop wireless networks subject to full interference. First, an optimization problem is formulated for maximizing the end-to-end throughput of FD relaying on a given, known path, considering the full interference model. A linear programming based solution is devised to obtain the optimal transmit power levels for FD relaying nodes on the path. Then, for joint power allocation and routing in an FD mesh network, Dijkstra's algorithm is modified by applying the proposed power allocation in the calculation of the path metrics. Via detailed numerical experiments considering different system parameters, such as network size, SI cancellation capability, maximum power level per node, it is shown that the proposed FD relaying with power control based on full interference model outperforms not only HD relaying, but also an existing FD relaying solution based on a single hop interference model. The amount of improvement by FD relaying depends on the system settings. For instance, for low power budget systems, HD throughput can be tripled, while for systems with high power budget, FD relaying achieves 80 percent higher throughput over HD relaying. When power control is combined with routing, the end-to-end throughput performance of the proposed FD routing solution again outperforms the existing solutions. Depending on the power budget, up to two times higher throughput is achieved over FD routing based on single hop interference, and HD routing can be improved by up to five times even for moderate SI cancellation levels. Our results suggest that employing proposed joint power allocation and routing scheme, migration to FD can be beneficial for home wireless mesh networks under full interference, especially for bandwidth-hungry applications, such as video streaming, gaming.

Keywords: Full-duplex communication, multi-hop communication, relaying, self-interference, full-duplex relaying, full-duplex routing.

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1. Introduction

Proliferation of mobile devices and explosion in data intensive applications have led to serious spectrum crunch and stimulated the pursuit of new wireless communication techniques to utilize the scarce wireless spectrum assets more efficiently. As one of the candidate technologies considered for next generation wireless systems, in-band full-duplex (FD) communication has been shown to have a great potential to alleviate this problem due to doubled spectral efficiency.

Unlike half-duplex (HD) radios, which need to transmit and receive at different times, or out-of-band full-duplex radios, which devote different frequency bands to transmission and reception, in-band FD radios are capable of transmitting and receiving at the same time, over the same frequency band, at the cost of self-interference (SI) that results. A long-held taboo in wireless communications was that a radio cannot simultaneously transmit and receive at the same frequency, due to the high SI observed at the receiver [1]. With the recently developed passive (antenna level) and active (analog and digital) interference cancellation techniques in radio design, successful FD communication has been demonstrated [2, 3]. As summarized in [4], since SI cannot be completely cancelled, FD is more suitable for low power, short range systems, such as small cells and wireless local area networks (WLANs).

In practical WLANs, especially in home networks, despite the Gbps level data rates provided to the home, throughput of some of the single hop direct connections can starve due to poor reception caused by severe attenuation effect of walls, floors etc. This situation can be improved by mesh networking, i.e., multi hop relaying, but the improvement of multi hop relaying in such scenarios is limited due to inter-node interference: As all nodes in the network hear each other, the channel is to be time shared between all the nodes during relaying in HD mode by the current radios. Consequently, the observed end-to-end throughput remains to be much lower than Gbps level provided at the ingress. Upgrading the radios by FD technology, each node can transmit to a node while receiving from another node, and by FD multi hop relaying, simultaneous transmissions can be enabled over all mesh links promising a potential for improved performance. However, SI on each FD node is to be added to the inter-node interference, resulting in a more complicated, full interference scenario, such as the physical model in [5].

In the literature, FD multi hop communication has been studied from various aspects: Authors in [6] consider 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 [7], 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

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Email addresses: `kudret@sabanciuniv.edu` (Kudret Akçapınar), `ogurbuz@sabanciuniv.edu` (Özgür Gürbüz), `tonguc@sabanciuniv.edu` (Tonguç Ünlüyurt) need for power control. In [8], 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. [9] provides performance comparison of FD and HD multi hop relaying, assuming equal transmit allocation. In [10], an optimal power allocation solution is proposed for FD multi hop networks, considering the interference from single hop neighbor nodes only. In [11], a medium access control (MAC) scheme with power control is proposed for a three node (two hop) FD network scenario, where the power control solution is based on a heuristic search for equalizing link rates.

In this paper, a power allocation solution is proposed along with routing for applying FD in multi hop wireless networks subject to full interference[1]. An optimal power allocation solution is devised for FD multi hop relaying on a known path of nodes, with the aim of maximizing the end-to-end throughput, considering full interference, i.e., both inter-node interference from all nodes and SI due to FD operation. Note that, the proposed linear programming based power allocation solution is general in that it applies to FD multi hop networks of any size. The power control solution is then applied into routing, where Dijkstra's algorithm is modified to incorporate the proposed optimal power allocations based on the full interference model.

Detailed simulations have been performed to investigate the performance of proposed power allocation and routing solutions, considering different system parameters, such as network size, SI cancellation capability, maximum transmission power as well as different channel conditions. Our results show that FD multi hop relaying with proposed 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. Optimizing power allocation according to the full interference model, the proposed FD multi hop relaying outperforms the solution based on one hop interference [10] by up to a factor of two. Applying power control jointly with routing under the full interference model, the proposed FD routing is shown to enhance the throughput of HD routing by a factor of up to five, and outperform FD routing based on one hop interference by a factor of two. Note that, the amount of performance enhancement depends on the power budget of the system and the presented results represent upper bound performance, still making the proposed joint power allocation and routing a promising solution for FD mesh networks under full interference.

The rest of the paper is organized as follows: In Section 2 the system model is provided. In Section 3 first the optimal power allocation problem is formulated and solved for FD multi hop relaying on a known path. Then, a routing scheme, which employs proposed power allocation is presented for FD mesh networks. Section 4 presents the performance results for both schemes. Section 5 provides conclusions and future research directions.

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[1] This work was presented in part at the First International Balkan Conference on Communications and Networking, BalkanCom'17 [12]

2. System Model

We consider a wireless mesh network with FD capable nodes, where a source node wishes to forward its messages to destination node in a FD fashion through some intermediate FD relays. An example FD relaying scenario is depicted in Figure 1. In this example network, a source node, say node 1, wishes to stream its data to a destination node, say node 10 possibly through some intermediate relays. FD relaying requires transmission and reception to be executed in the same frequency and at the same time, eliminating the necessity for time or frequency division duplexing. For instance, node 5 receives from node 2, while simultaneously transmitting to node 9 at the same carrier frequency. Obviously, numerous possible paths exist between the source and the destination nodes. In Figure 1, one alternative path is marked, where the relaying nodes are colored in green and the idle nodes are colored in red.

All nodes are FD capable with a single antenna FD radio as in [13], so that they can simultaneously transmit and receive data over the same carrier. Each node has SI cancellation capability of the same degree. A one-way single data flow is assumed between source and destination nodes, so that nodes which are not included in a selected path are enforced to remain idle, hence inter-node interference is only due to the actively transmitting FD nodes on the same path. We also assume that all nodes in the network hear each other and we also presume that channel state information (CSI) between all pairs of nodes is available at the source node.

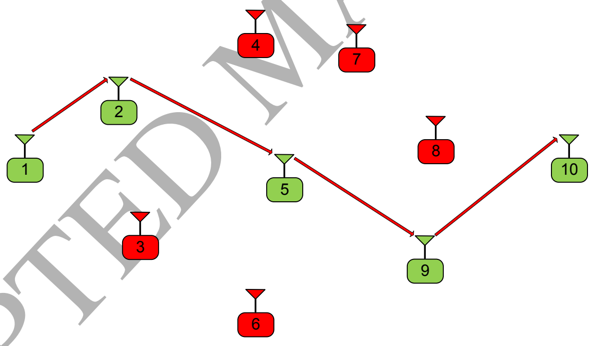

Figure 1: An example route in FD mesh network

3. Joint Power Allocation and Routing for FD Networks

The FD relaying task in mesh networks poses two major problems: The first one is to find the best route between source and destination nodes, and the second problem is to find a transmission power policy for the nodes on the selected route. Both problems becomes more complicated in the case of full interference, where each node in the network hears all other nodes. In this paper, aiming to maximize the end-to-end throughput, we firstly focus on the optimal transmission power allocation problem for FD relaying over a given path. Then, we address how proposed power allocation policy can be integrated with routing, resulting in a joint power allocation and routing solution for FD networks.

3.1. Optimal Power Allocation for FD Relaying on a Known Path

We consider a chain network such as the one shown in Figure 2, where a source node wishes to deliver a data stream to a destination node over a given path of multiple relay nodes. Except for the source node (labeled as node 1) performing only transmission and the destination node (labeled as node N) performing only reception, the intermediate nodes are all relaying data in FD mode.

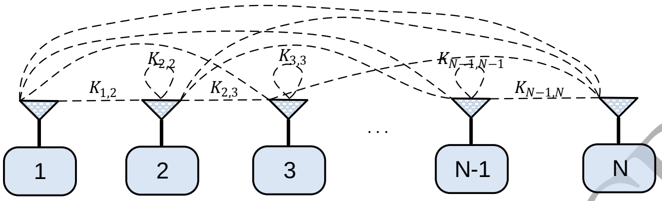

Figure 2: FD multihop relaying network

The data flow path 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 to the next node along the path, while receiving data from the previous node. Also, it is assumed that all transmissions are synchronized, and the delays for decoding and forwarding are ignored.

Practically, FD communication is imperfect, since SI cannot be cancelled completely at the FD nodes. The effect of residual SI is modeled as the transmit power level attenuated by a constant factor, β, as in [10]. The channel gain between any two nodes i and j is denoted by $K_{i,j}$, as shown in Figure 2. Letting an arbitrary node i, ($i \in \{2, \ldots, N\}$) have a maximum transmission power P_{max}, and defining the transmission power level of node i as $P_i \leq P_{max}$, the Signal-to-Interference-Plus-Noise Ratio (SINR) observed at node i is calculated as:

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

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 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 (AWGN) with the same variance of σ^2, as shown in the first term in the denominator of (1). Also, identical radios are assumed for all nodes, so that same SI suppression factor, β and maximum transmission power, P_{max} are applied for all nodes.

At this point, for the brevity of the rest of the analysis and formulation of the optimization problem, we name 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.) Hence, the achievable rate observed at node i received from the transmission of node $(i-1)$ can be written as:

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

The end-to-end throughput, R is equal the rate of the bottleneck link, found as

$$R = \min\{R_{1,2}, R_{2,3}, \ldots, R_{N-1,N}\}. \tag{3}$$

Considering the streaming scenario in Figure 2, increasing the transmit power level of a node enhances the power of the intended signal at the next node along the path, increasing the numerator of the link SINR; however the amount of residual SI as well as the level of inter node interference to other nodes are also increased, affecting all the link rates and the end-to-end throughput, R. This trade off can be addressed by optimally controlling the transmission power levels of all nodes, which can be formulated by the following optimization problem:

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

In this work, we propose a linear programming based solution method for obtaining the optimal power allocations, i.e., P_i values $\forall i \in \{1,\ldots,N-1\}$, as described next.

Letting $z = \min_{i\in\{2,\ldots,N\}}\{R_{i-1,i}\}$, we can divide the whole problem in (4) into $N-1$ distinct problems since the minimum should occur in one of the links $(k-1,k)$ for some $k \in \{2,\ldots,N\}$. Each of these problems can be solved separately. For instance, let us consider the following Problem k, with $k \in \{2,\ldots,N\}$, where the minimum occurs at link $(k-1,k)$:

$$\begin{aligned} z_k^* = &\max z \\ &\text{s.t.} \\ &\quad z \le R_{i-1,i}, \forall i \in \{2,\ldots,N\} - \{k\} \\ &\quad z = R_{k-1,k} \\ &\quad 0 \le P_i \le P_{max}, \forall i \in \{1,\ldots,N-1\}. \end{aligned} \tag{5}$$

Then, z^* can be computed as $\max\{z_2^*, z_2^*, \ldots, z_N^*\}$, so it is sufficient for us to solve Problem k efficiently. Below, we describe how we find an exact solution to Problem k which leads to an exact solution to the original optimization problem (4). The constraints of Problem

k are non-linear. Yet, for a fixed z, one can determine if $z_k^* \geq z$, by checking whether the linear programming model defined in (6) has a feasible solution as explained below. By substituting the rate expression from equation (2) into the first two constraints of (5), the constraints of problem k can be rewritten as:

$$\begin{aligned}
&(2^z - 1)\left(\sum_{\substack{j=1\\ j\neq i-1}}^{N-1} K_{j,i}P_j\right) - K_{i-1,i}P_{i-1} \leq (1-2^z)\sigma^2 \\
&\qquad\qquad\qquad \forall i \in \{2,\dots,N\} - \{k\} \\
&(2^z - 1)\left(\sum_{\substack{j=1\\ j\neq k-1}}^{N-1} K_{j,k}P_j\right) - K_{k-1,k}P_{k-1} = (1-2^z)\sigma^2 \\
&\qquad\qquad 0 \leq P_i \leq P_{max}, i \in \{1,2,\dots,N-1\}
\end{aligned} \tag{6}$$

For a fixed z, all the inequalities in (6) are linear and $z_k^* \geq z$ if there exists a power allocation vector P_i, $i \in \{1,2,\dots,N-1\}$ satisfying (6). This can be checked by any linear programming solver. Then, it is possible to find the optimal value for Problem k, $\forall k \in \{2,\dots,N\}$ by conducting a search over the possible objective function values. For the search procedure, we set the limits of the search interval as, $z \in [0,\gamma]$, where γ is defined as:

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

The search starts by setting z equal to the middle of the initial interval, i.e. $z = \gamma/2$ 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. In the next iteration, similarly lower and upper bounds of search interval are updated. This process is continued until the length of search interval drops below a certain threshold value, ϵ. Therefore, finding the optimal power levels require solving $\log(\gamma/\epsilon)$ linear programming problems.

Note that, the optimal power allocations are obtained for a given set of values of $K_{i,j}$, which are assumed to be provided or estimated as the channel state information (CSI). When the channel gains in (1) change in time, the new CSI can be obtained and communicated by a MAC scheme (such as [11]) that operates in accordance with the channel coherence time. At the expense of the introduced overhead, the new CSI can be used in calculating the new optimal power allocations by re-solving the problem in (4). In this work, we consider an ideal operation with zero overhead, in an effort to observe the performance upper bound to be achieved by FD.

3.2. FD Routing with Proposed Power Allocation

Optimal FD routing, which is determining the path with the maximum end-to-end throughput in an FD mesh network is difficult to solve and requires an exhaustive search, since the objective function in this problem does not have monotonic nature, unlike the shortest path problem. This is because, each time a node is added to a path, due full-interference, the end-to-end rate of the links between the nodes that have been previously placed on the path may change. On the other hand, in the shortest path problem and the conventional Dijkstra algorithm, the objective function is to minimize the sum of the link costs [14], which is monotonic, and adding a new node to a path does not alter the preceding cost(s) on the path.

In this paper, as a practical solution for FD routing, we propose a sub-optimal, heuristic solution, which is a modified version of Dijkstra's shortest path algorithm. The modification is that the path metrics are calculated using the proposed optimal power allocation based on the full interference model. In the proposed FD routing algorithm, the link costs are the end-to-end rates up to a given node, calculated using optimal power allocations by solving (4), and the objective function is maximizing the end-to-end throughput to reach the destination. The pseudo code of the proposed FD routing algorithm is given in Algorithm 1.

Algorithm 1: FD routing algorithm with proposed power allocation

```
Input: $K_{i,j}, \forall i, j \in \{1, \ldots, N\}$, $P_{max}$, $\sigma^2$
Output: Route defined by $pred$
$\mathcal{S} = \emptyset, \overline{\mathcal{S}} = \{1, \ldots, N\}$;
$R(1) = \infty$, $pred(1) = 0$ ;
$R(i) = 0, \forall i \in \{2, \ldots, N\}$;
while $N \in \overline{\mathcal{S}}$ do
    $i = \underset{k \in \overline{\mathcal{S}}}{\operatorname{argmax}} R(k)$
    $\overline{\mathcal{S}} = \overline{\mathcal{S}} - \{i\}$ ;
    for $j \in \overline{\mathcal{S}}$ do
        Calculate $R'(j)$ by solving (4);
        if $R(j) < R'(j)$ then
            $R(j) = R'(j)$;
            $pred(j) = i$;
        end
    end
end
```

Here, $R(i), \forall i \in \{1, \ldots, N\}$ denotes the current rate of node i and $R'(j), j \in \overline{\mathcal{S}}$ denotes the end-to-end throughput of the path from the source extending to node j, passing through node i, where i is the newly included node in set $\mathcal{S}$. $R'(j)$ is calculated using (3), with individual link rates computed using (2) and power levels set according to the optimal power allocation solution obtained from (4). $pred(i)$ denotes the predecessor of the node i in the respective route.

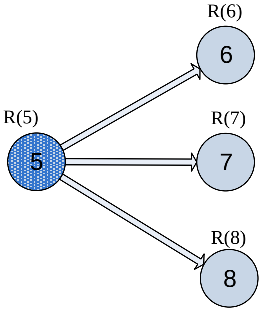

Figure 3: Example for updating costs in proposed FD routing algorithm

Figure 3 shows an example case for updating costs of nodes in the proposed FD routing algorithm. Assume that, at an intermediate step during the progression of the algorithm, node 5 is newly selected and included in the set, $\mathcal{S}$ and nodes 6, 7 and 8 are the remaining nodes in set $\overline{\mathcal{S}}$, as shown in Figure 3. Assume also that predecessor nodes of node 5 had been previously selected as $\{1, 3, 4\}$. At this point, the proposed FD routing algorithm calculates the following costs: $R(1, 3, 4, 5, 6)$ for node 6, $R(1, 3, 4, 5, 7)$ for node 7 and $R(1, 3, 4, 5, 8)$ for node 8, where $R(1, 3, 4, 5, i)$ denotes the end-to-end throughput of FD relaying over the route $\{1, 3, 4, 5, i\}$. In the calculation of $R(1, 3, 4, 5, i)$, power levels of the FD nodes are optimally calculated by our power control solution from (4). If the updated costs are larger than the current costs of nodes $6, 7$ and 8, the costs of these nodes are updated as the newly calculated costs, with the predecessor of the nodes being updated to 5. For example, let us assume that $R(1, 3, 4, 5, 6) > R(6)$, then $R(6)$ is updated as $R(1, 3, 4, 5, 6)$ and predecessor of node 6 is changed to 5, i.e. $pred(6) = 5$. The algorithm terminates when destination node is included in set $\mathcal{S}$, as in Dijkstra's algorithm. Once the route is determined, the power levels for the nodes on this path are assigned according to our proposed power allocation solution.

An iteration by iteration progression of the FD routing algorithm for a small network is also given in Figure 4. The algorithm first initializes the following: $\mathcal{S} = \emptyset, \overline{\mathcal{S}} = \{1, \dots, N\}, R(1) = \infty, pred(1) = 0 \; R(i) = 0, \forall i \in \{2, \dots, N\}$. Next, it chooses the node with the highest rate in $\overline{\mathcal{S}}$. The chosen node is added to set $\mathcal{S}$ and deleted from $\overline{\mathcal{S}}$. In this example, this corresponds to node 1 in the first iteration. The rates of the other nodes are updated, if their current link rate obtained by the inclusion of node 1 is larger than their previous values. Since in the first iteration $R(2), R(3)$ and $R(4)$ are all 0, their values are updated to positive non-zero values. In the following iterations, similar updates are made and the algorithm is terminated in the fourth iteration when all the nodes are included in $\mathcal{S}$. We envision that the routing algorithm is to be executed at the source node (prior to data streaming) on the selected path and data is to be relayed in FD mode using source routing, while the transmission power levels are set according to the proposed allocation.

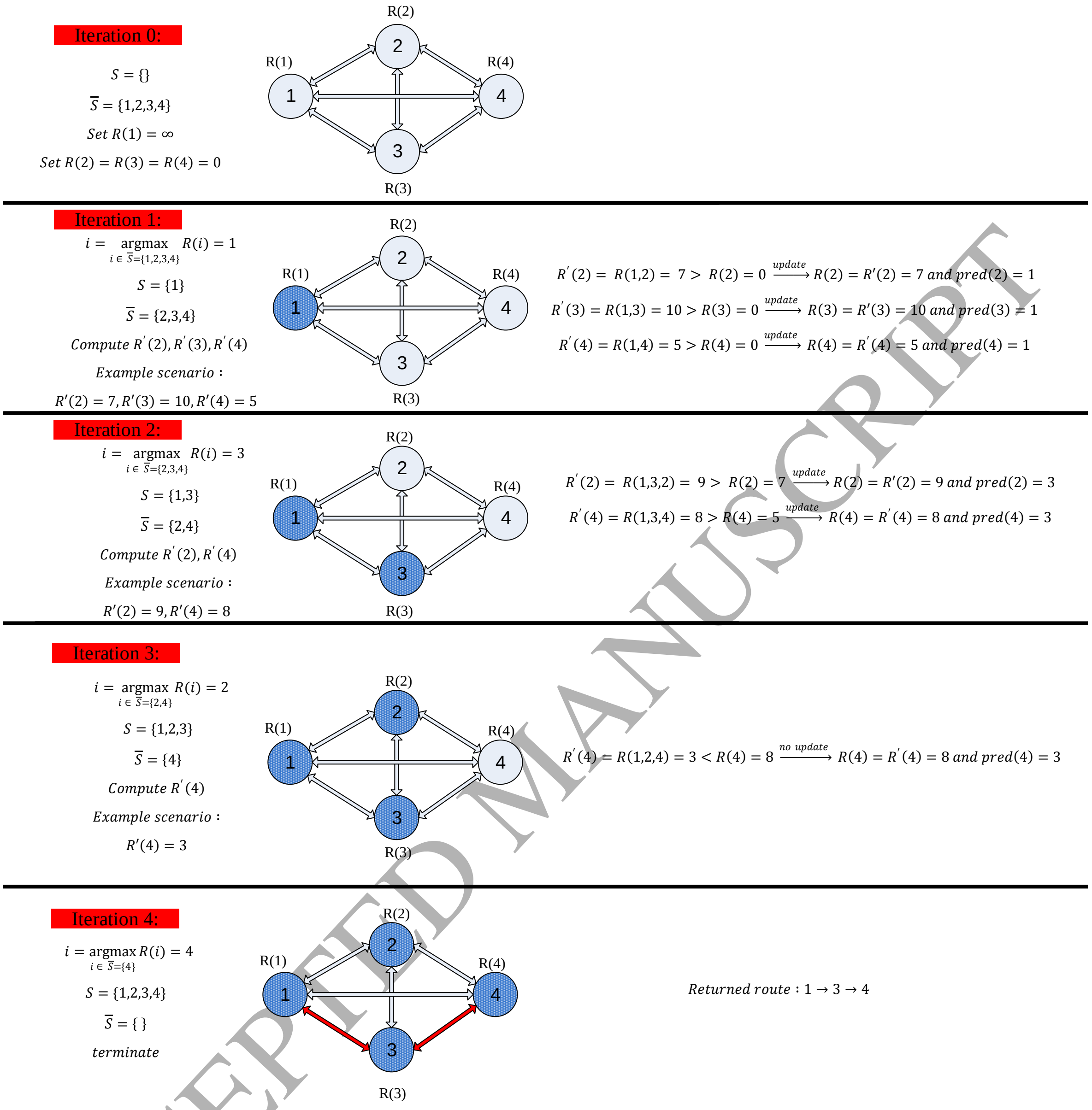

Figure 4: Iteration by iteration progression of the proposed FD routing algorithm on a small network

The proposed FD routing algorithm differs from Dijkstra's algorithm in updating the costs of the selected nodes, as illustrated by Figures 3 and 4. Our solution also differs from FD routing in [10], as authors in [10] assume interference from only one hop neighbors, while we assume full interference, where each node can hear all nodes in the network, which is typical for home wireless networks. The single hop interference assumption in [10] is not only far from reality, but also their recursive solution is no longer valid in the case of full interference. On the other hand, our solution considering full interference is applicable to the one hop interference case.

Considering the complexity of the proposed FD routing algorithm, the complexity of routing alone is $O(n^2)$ as our network model is represented by an all-linked graph due to the full interference model. In each step of routing, $R'(j)s$ are calculated based on the search algorithm. Assuming the initial length of the search interval is γ, and that the algorithm terminates when the length of the current interval falls below a certain interval length, ϵ, the total number of iterations required for the search of optimal power solution is given by $\log\left(\frac{\gamma}{\epsilon}\right)$. In each iteration of this binary search, feasibility of the current constraints is checked by an algorithm that solves linear programming problems. Hence, the total complexity of the proposed joint FD power allocation adn routing algorithm amounts to solving $O(\log\left(\frac{u}{\epsilon}\right) n^2)$ linear programming problems.

4. Performance Analysis

In this section, we present the end-to-end throughput performance of FD multi hop relaying with proposed power allocation, followed by the performance of FD routing with proposed power allocation. In all our numerical simulations performed in MATLAB, the channel gains are determined based on the generalized path loss model, $K_{i,j} = d_{i,j}^{-\alpha}$ for $i \neq j$, where $d_{i,j}$ is the distance between nodes i and j, similar to the numerical experiments in [10]. The propagation environment is assumed to be abundant of obstacles hindering the line of sight communication and leading to heavy path-loss attenuation (high α). This necessitates multi hop relaying and matches well with the scenario of home WiFi networks, where all nodes can hear each other, but multi hop relaying is necessary for higher end-to-end throughput. The system parameters used in the simulations are set as shown in Table 1, unless varied as specified in the experiments.

Table 1: System Parameters

Parameter	Description	Value
α	Path loss exponent	4
β	SI suppression factor	-80 dB
P_{max}	Maximum transmission power per node	0 dBm
σ^2	Average noise power	-70 dBm

4.1. FD Relaying with Optimal Power Allocation

In this section, the performance of proposed FD relaying with optimal power control based on full interference is compared with the performance of FD multi hop relaying with power control based on single hop interference [10], HD multi hop relaying[2] and single hop direct transmission.

In the simulation experiments, nodes are placed on a straight line with equal spacing as in [15, 16]. Source and destination nodes are positioned 0 m and 100 m, respectively,

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[2] An HD node either transmits or receives at a time, and time division multi access (TDMA) is assumed for the coordination of the transmissions of HD relay nodes.

other nodes are placed with a spacing of $\frac{100}{N-1}$ m. We investigate the effect of number of nodes (i.e node density since total range is fixed), transmission power budget of nodes and self-interference cancellation capability of the nodes on the end-to-end throughput.

Figure 5 shows the end-to-end throughput with respect to the network size, N. Here, increasing N implies the increasing network density as the source to destination node distance is kept fixed. It can be seen that multi hop communication even in HD mode surpasses the throughput of direct transmission, which is poor due to heavy path loss. FD multi hop relaying with proposed power control improves HD multi hop, also outperforming the scheme in [10], which takes into account the interference of only single hop neighbors.

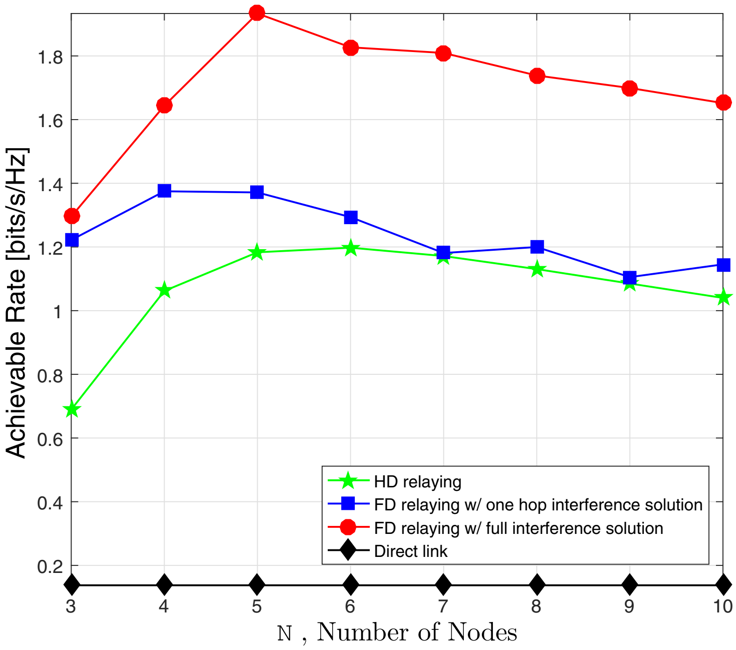

Figure 5: Throughput vs network size

Next, the effect of the power budget, i.e. maximum transmission power per node, P_{max} is investigated for a network of 10 nodes. As depicted in Figure 6, where the power level is expressed in dBm, the performance of FD multi hop relaying scheme in [10] degrades significantly after a certain P_{max} level, as that solution considers the interference of single hop neighbors, although in reality, the network is in a full interference scenario. Consequently, the gain of our FD multi hop relaying scheme over [10] increases with the increasing power budget. Actually, FD multi hop relaying with the proposed power allocation offers the highest throughput for all power levels. For low power budget, proposed FD multi hop relaying doubles the throughput of HD multi hop relaying. The improvement over HD gets smaller as the power budget is increased. Obviously, transmitting with higher power level engenders higher residual SI as well as higher inter node interference, resulting in smaller performance improvement over HD.

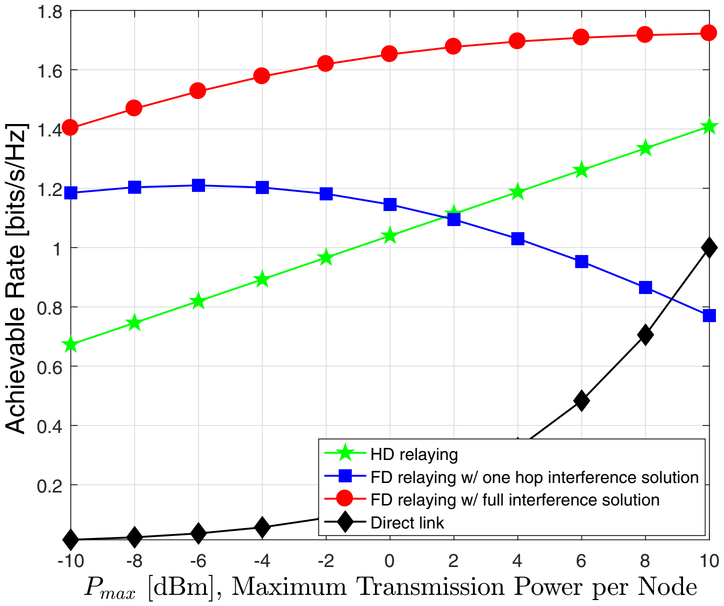

Figure 6: Throughput vs power budget, P_{max}

In Figure 7, the end-to-end throughput is observed as a function of the amount or level of SI suppression, measured as $|\beta|$ (in dB) for 10 nodes. It can be seen that, the performance of both FD relaying schemes ameliorate with stronger SI suppression. However, the throughput remains constant after a certain level of SI, since residual interference approaches to zero.

In the next experiment, FD nodes are randomly, uniformly distributed in the range of 100 meters to account for distance variations. Also, in order to study the effect of channel variations, Rayleigh fading is modelled via exponentially distributed unit channel gains, which multiply the coefficients reflecting path loss. In order to obtain the mean end-to-end throughput, we have calculated the averages over 1000 realizations. The results are presented in Figure 8, where it can be seen that HD outperforms FD when $N > 3$. The reason why HD outperforms FD relaying is because all nodes are enforced to be included in the relaying path. However, when some nodes happen to come too close to each other or fading happens to make some link(s) strong/weak, some nodes should be excluded in the path for better end-to-end throughput. Getting the best out of FD relaying under full interference requires a routing strategy, which can determine the nodes to be included in the relaying path.

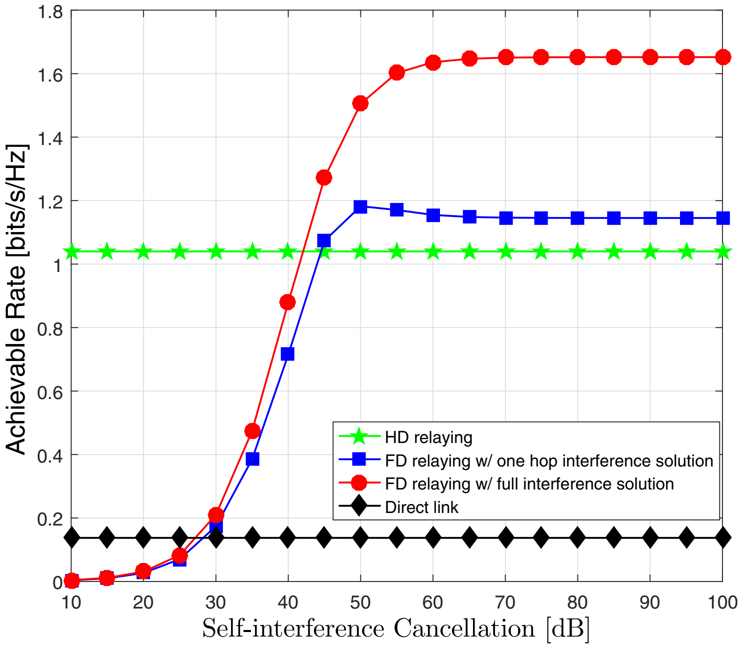

Figure 7: Throughput vs SI suppression level, $|\beta|$

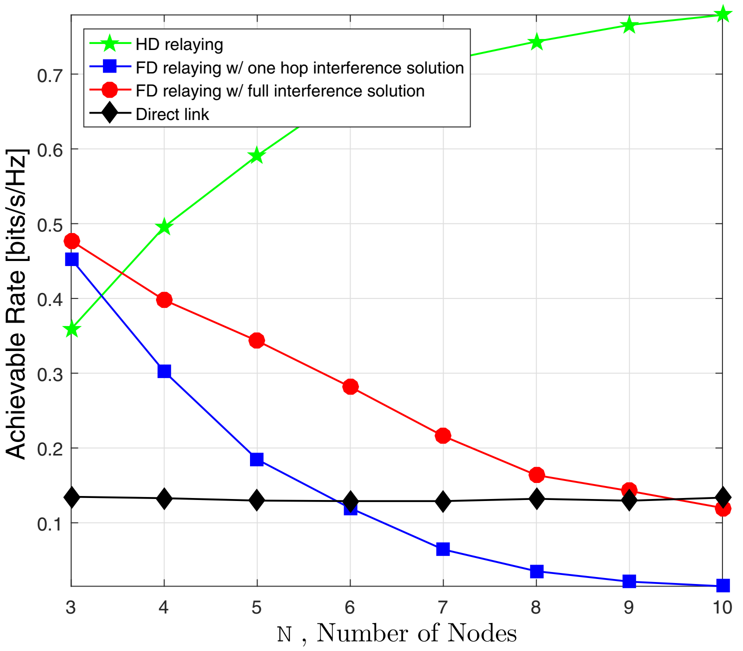

Figure 8: Throughput vs network size, N

Also, while investigating this scenario, we have observed that even when channel gains are different for each link, our power control solution results in equalized link rates by fine tuning of the transmission power of the nodes. Irrespective of whether the channel gains are equal or not, it turns out that the end-to-end throughput of FD multi hop relaying is maximized only when the rate of all links in the network are equalized. This is consistent with the solution in [10], as well as the earlier works on two hop relaying, [17] and [18]. In those works, it is shown that Nash equilibrium is reached when the link rates are equal. Link rate equalization approach is also presented in [11], where a (heuristic) solution is proposed for transmission powers in the two hop case, while our power allocation solution applies for a multi hop FD network of any size.

4.2. FD Routing with Proposed Power Allocation

In this section, we present the performance of the proposed FD routing algorithm with proposed power control based on full interference model, in comparison to FD routing with power control based on one hop interference [10], HD routing and direct transmission. To make a fair comparison, we consider a similar routing algorithm for HD. In HD routing, the costs are updated, so that the transmission durations of the links are optimally allocated as new nodes are added to the route.

For the simulations, the same system parameters given in Table 1 are applied. For the network scenarios, a square zone with a side length of $100m$ is considered. The source node is positioned at location (0,100), the destination node is placed at location (100,0), and the intermediate nodes are randomly sprinkled in this zone, such that x and y coordinates of the nodes are each uniformly distributed in [0,100]. 1000 realizations of this network are simulated for each routing algorithm to obtain average end-to-end throughput.

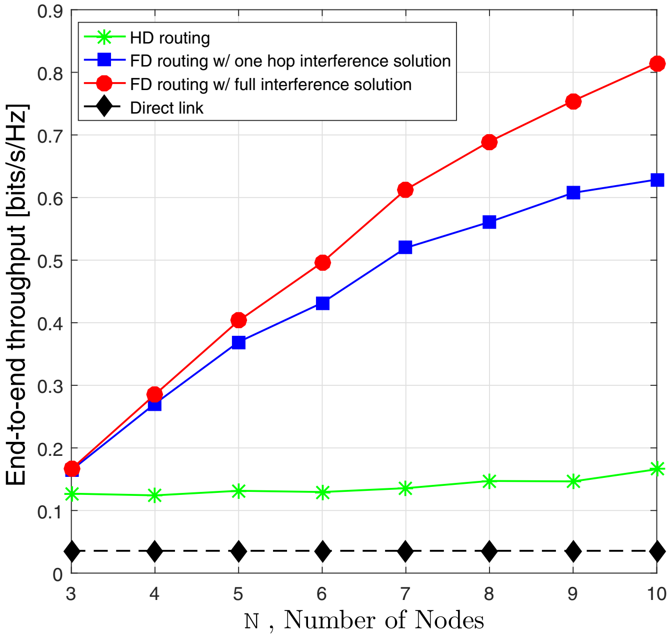

Figure 9: Throughput vs network size

In Figure 9, we observe the end-to-end throughput as a function of the network size, i.e. number of nodes dropped into the area. The results suggest that our full interference based FD routing gives the highest throughput among all schemes. As the network size is increased, both FD solutions provide higher throughput, while HD routing is slightly increased and direct transmission remains unchanged. Proposed FD routing provides up to five times higher throughput relative to HD routing for the settings in Table 1.

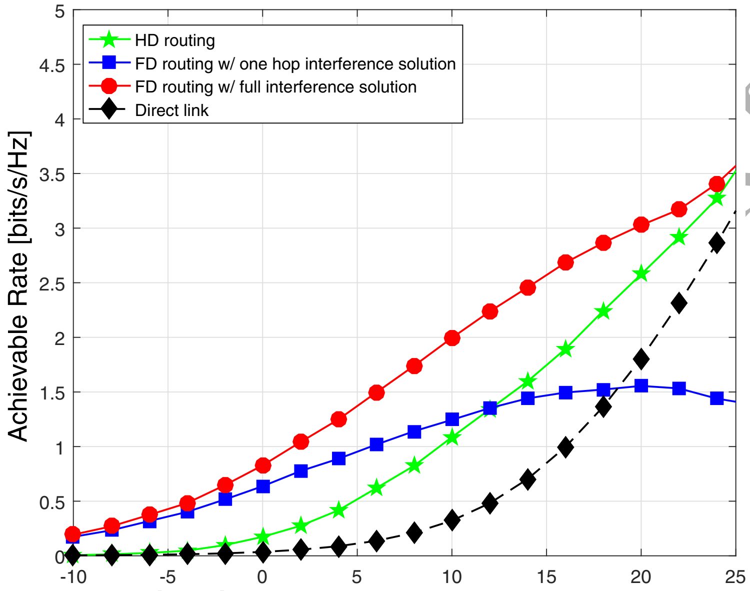

Figure 10: Throughput vs power budget, P_{max}

Next, in Figure 10, the performance of proposed FD routing is observed as a function of the power budget, i.e., maximum transmission power per node, P_{max}. As clearly seen from this figure, proposed FD routing offers the best performance for all power levels. Note also that, the performance of one hop interference based power control solution in [10] decreases after a certain power level, similar to the earlier results in Figure 6. The gain of proposed FD routing based on full interference provides over this scheme increases up to a factor of two as can be seen from the figure.

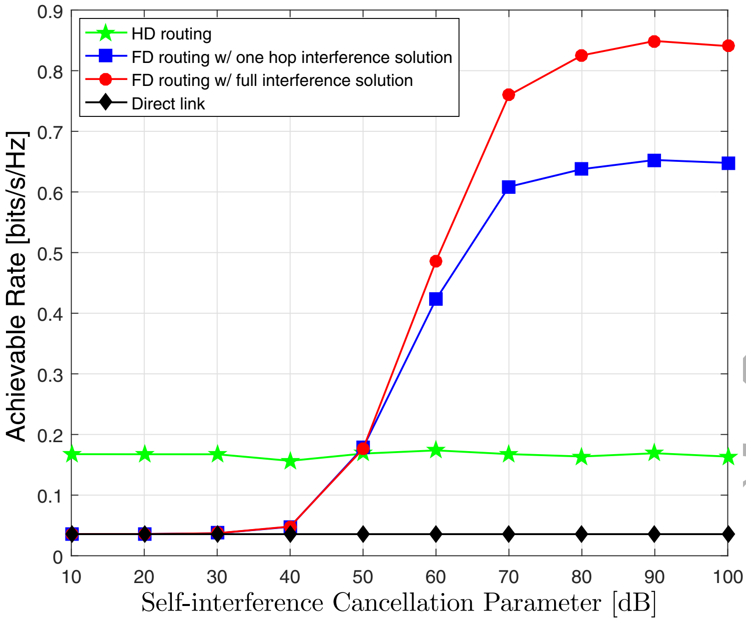

Figure 11: Throughput vs SI cancellation

Finally, in Figure 11, we investigate the end-to-end throughput of FD routing as a function of SI cancellation capability. Notice that for the SI suppression level smaller than about $50dB$, HD performs better than both FD strategies. We also observe that increase in β does not improve the throughput after $80dB$ cancellation since the SI cancellation performance converges to ideal (perfect) cancellation. For sufficient SI cancellation, our FD routing solution provides 30% improvement over [10] for the power setting in Table 1, and it outperforms HD transmission by a factor of five.

5. Conclusions

We have presented a linear programming based power allocation solution for maximizing the end-to-end throughput of FD relaying for multi hop networks under full interference model. Our numerical experiments show that, on a given path, FD multi hop relaying with the proposed power allocation performs significantly better than HD multi hop relaying. More specifically, for the set of observed parameters, HD throughput can be tripled for low power budget FD systems, while for systems with high power budget, FD relaying achieves 80% higher throughput over HD relaying. Since proposed power allocation considers the full interference model, proposed FD relaying significantly outperforms FD relaying based on one hop interference.

Secondly, we have incorporated the proposed power control solution in routing of FD multi hop networks under full interference. We have compared the performance of the proposed FD routing solution with traditional HD routing and FD routing based on single hop interference. Our experiments have demonstrated that the proposed FD routing based on full interference provides up to two times higher throughput over FD routing based on single hop interference, and the gain of proposed FD routing over HD routing can be as high as five times, even for moderate SI cancellation levels. Note that, the amount of performance enhancement by FD depends on the power budget of the system. It is also worthwhile to note that the presented results reveal the potential and upper bound performance for FD routing, as the overhead of medium access is not considered. A natural future research direction is design of a cross layer MAC protocol, which can realize the proposed joint FD power control and routing algorithm while enabling and making use of CSI updates.

6. Acknowledgements

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