Multi-hop Relaying with Optimal Decode-and-Forward Transmission Rate and Self-Immunity to Mutual Interference among Wireless Nodes

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***Abstract*—In this paper we show that multi-hop relaying with immunity to mutual interference among relays can be realized in multi-hop ad hoc wireless networks with full-duplex decode-and-forward relays that exploit appropriate packet encoding and successive interference cancellation. This resolves fundamentally the mutual interference challenge involved in multi-hop wireless network research. Based on this interference immune phenomenon, a relay selection algorithm is developed to find the optimal hop count and the optimal relays that maximize source-destination decode-and-forward transmission rate. The algorithm constructs the optimal multi-hop paths from a source node to all other network nodes simultaneously with a quadratic complexity $O(N^2)$, where N is the network size. This algorithm is efficient for wireless networks with arbitrary size, including extremely large sizes, and can potentially play a fundamental role in exploring multi-hop wireless networks. Surprisingly, this wireless networking algorithm is similar to the well-known Djikstra's algorithm of wired networks. Simulations are conducted to demonstrate the efficiency and the superior performance of the new algorithm.**

***Keywords*—Wireless network, multi-hop relay, transmission rate, throughput optimization, efficient algorithm**

I. Introduction

For wireless ad-hoc networks that consist of a large number of wireless nodes, network capacity is a long-standing open problem. This problem is critical because large networks generate massive amount of information for communication, but the communication capacity per node reduces with network size or number of network nodes [1]. Wireless network capacity has been a focused research subject for decades, with many important theoretical progresses achieved. One of them is the scaling laws of large wireless networks with infinite size [1]-[3]. Nevertheless, network capacity is still absent for most wireless networks.

Even the potentially simpler but fundamental networking problem, i.e., selecting optimal relays to maximize transmission rate between a source node and a destination node via multi-hop relaying, remains challenging. In wired networks, well-known algorithms such as Dijkstra's Algorithm can be used for multi-hop path construction and optimization [4]. In wireless networks, however, the problem becomes significantly more challenging because the broadcasting nature of wireless transmissions creates complex mutual interference among wireless nodes. Wireless nodes interfere with each other when transmitting, but can potentially help each other via cooperative transmission and multi-hop relaying. Competition and cooperation among wireless network nodes make it challenging to optimize hop selection and capacity optimization.

Theoretically, wireless network capacity expressions or optimal multi-hop relay selection algorithms can be derived based on exhaustive search over all possible node combinations [5]-[7]. Unfortunately, exhaustive search has prohibitively high computational complexity that is exponential in network size.

Due to this complexity hurdle, most network capacity research is limited to very small networks with one or two hops [8]. Most multi-hop relay study is limited to a few fixed relaying nodes only [9]. Hop count optimization and multi-hop relay selection have been studied in [10][11] but for a special linear network with fixed relaying nodes only. The exponentially complex relay selection problem is still an open challenge.

Wireless network routing protocols avoid such mutual interference issues of the physical-layer by working over a transparent physical-layer [12]-[14]. Therefore, they can not resolve the mutual interference challenge, nor achieve the optimal network capacity. In fact, their major purpose is to find a multi-hop forwarding path from the source to the destination in face of node movement and link unreliability. The optimization of path capacity or network capacity is only secondary or is given up due to complexity. There is another class of methods that depend on sophisticated simulation techniques for network optimization, such as evolutionary computing [15][16].

Noticing the key issue of interference, we show in this paper that full-duplex decode-and-forward relaying, when combined with appropriate encoding and successive interference cancellation, can make multi-hop relays immune to mutual interference. In other words, the rate of each relay is not affected by the inevitable mutual interference among relay nodes. This resolves fundamentally the mutual interference issue, and leads to efficient algorithms for optimal relay selection in arbitrarily large wireless networks.

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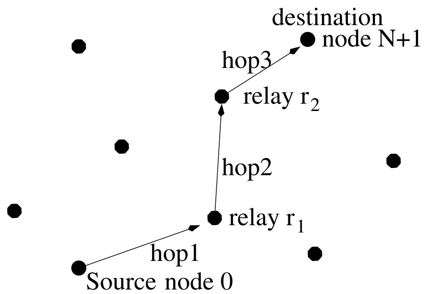

Fig. 1. A wireless network where the source node 0 transmits packets to the destination node $N+1$ via a 3-hop relaying path with relays r_1 and r_2.

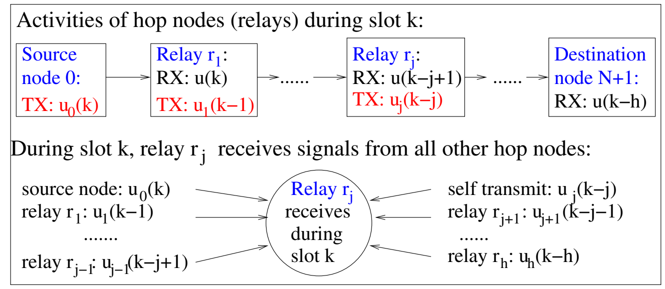

Fig. 2. Transmission and receiving schedule of multi-hop relaying. RX denotes receiving and decoding. TX denotes transmitting.

The organization of this paper is as follows. In Section II, we give the multi-hop wireless network model. In Section III, we show the interference immune phenomenon in multi-hop wireless networks. Then we develop a new multi-hop relay selection algorithm in Section IV. Extensive simulations are conducted in Section V. Conclusions are given in Section VI.

II. Multi-hop wireless network model

We consider a wireless network with $N+2$ nodes. For simplicity, we consider only one transmission path from a source node, which we denote as node 0, to a destination node, which we denote as node $N+1$. Any of the other N nodes, which we denote as node 1 to node N, may be selected as relays. In Fig. 1, a 3-hop transmission path is illustrated.

The problem considered in this paper is the optimization of hop count and relay nodes selection. The objective of such optimization is to maximize the source-destination transmission rate. Let the index set $\mathcal{N} = \{1,2,\cdots,N\}$ denote all candidate relay nodes. Let the optimal hop count (number of hops) be $h+1$, where $0 \le h \le N$ and $h=0$ means direct source-destination transmission without relaying. We need to select a relay node r_j for each hop j, where $r_j \in \mathcal{N}$, $1 \le j \le h$, to maximize the source-destination multi-hop transmission rate. For notational simplicity, we define $r_0 \stackrel{\triangle}{=} 0$ and $r_{h+1} \stackrel{\triangle}{=} N+1$.

We consider causal full-duplex decode-and-forward relays. While a relay is receiving a packet, it can transmit simultaneously another packet that it has already decoded. This relay model is adopted widely in information theory research to study decode-and-forward transmission rate, i.e., the transmission rate that is achievable via the decode-and-forward relaying strategy [7][10]. The full-duplex assumption is not just a theoretical convenience. Its practical implementation is also promising, as demonstrated by a number of full-duplex relay research activities in recent years [17]-[19].

We adopt a slotted multi-hop packet forwarding scheme. During slot k, the source node r_0 encodes a packet $\mathbf{u}(k)$ into transmission signal $\mathbf{u}_0(k)$ and transmits the signal $\mathbf{u}_0(k)$. Each relay r_j receives (and decodes) a packet $\mathbf{u}(k-j+1)$ while transmitting simultaneously the signal $\mathbf{u}_j(k-j)$, which is encoded from the packet $\mathbf{u}(k-j)$ that it received and decoded during previous slot. The destination node r_{h+1} receives (and decodes) the packet $\mathbf{u}(k-h)$. This procedure is illustrated in Fig. 2 (top).

With this scheme, one packet, e.g., $\mathbf{u}(k-h)$, is forwarded from the source node to the destination node in each slot. For each specific packet, e.g., $\mathbf{u}(t)$, it is received (and decoded) by each relay node r_j in slot $t+j-1$, and the relay node r_j re-encodes it into transmission signal $\mathbf{u}_j(t)$ and transmits this signal $\mathbf{u}_j(t)$ in slot $t+j$.

Note that the causality assumption preserves proper multi-hop delay, i.e., the larger the hop count $h+1$, the larger the delay, which is another important feature of wireless multi-hop networks besides transmission rate.

Due to the broadcasting nature of wireless transmissions, each hop node r_j, $1 \le j \le h+1$, receives the summation of all transmitted signals

$$\mathbf{x}_j(k) = \sum_{i=0}^{h} \sqrt{P_{r_i} G_{r_i,r_j}} e^{\jmath \theta_{r_i,r_j}} \mathbf{u}_i(k-i) + \mathbf{v}_j(k), \tag{1}$$

where P_{r_i} is the transmission power of the node r_i, $\sqrt{G_{r_i,r_j}} e^{\jmath \theta_{r_i,r_j}}$ is the instantaneous propagation channel coefficient from the transmitting node r_i to the receiving node r_j, $\jmath = \sqrt{-1}$, and $\mathbf{v}_j(k)$ is additive white Gaussian noise (AWGN). $\mathbf{x}_j(k)$, $\mathbf{u}_i(k)$ and $\mathbf{v}_j(k)$ are vectors containing all the samples in the slot k. The signals are illustrated in Fig. 2 (bottom).

We assume complex flat fading channels with gain $G_{i,j}$, zero-mean AWGN with power σ_j^2, and individual relay power constraint $0 \le P_j \le P_j^{\max}$. All encoded signals $\mathbf{u}_j(t)$ have unit power. We also assume that all channel coefficients and encoding rules are public knowledge.

In the wireless network model, we have considered two special properties of wireless networks: mutual interference and cooperation (via broadcasting and relaying) among nodes. However, there is only one relay in each hop, which means that we do not consider directly other cooperative transmission strategies that transmit a packet simultaneously by multiple relays in a hop. In Section IV, we will show that cooperative transmission involving multiple decode-and-forward relays in a hop is no better than the single relay transmission scheme used in our model. On the other hand, we limit our consideration to decode-and-forward relaying only in this paper, and exclude other relaying strategies such as amplify-and-forward relaying.

III. Multi-hop relaying that is immune to mutual interference

Without loss of generality, let us consider the operation of the relay r_j, which needs to process its received signal (1). Because the relay r_j has full knowledge of packets transmitted by itself and by relays in its following hops, it can subtract

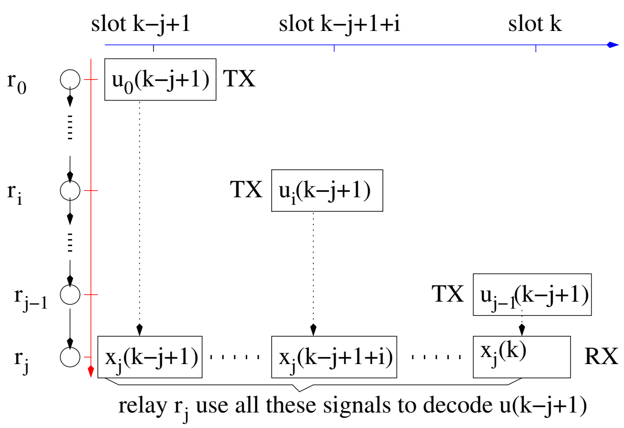

Fig. 3. During slot k, the relay r_j uses all the signals received during the past j slots to decode the packet $\mathbf{u}(k-j+1)$.

signals $\mathbf{u}_i(k-i)$, $i=j,j+1,\cdots,h$, from the mixture (1). The received signal (1) can thus be reduced to

$$\hat{\mathbf{x}}_j(k)=\sum_{i=0}^{j-1}\sqrt{P_{r_i}G_{r_i,r_j}}e^{\jmath\theta_{r_i,r_j}}\mathbf{u}_i(k-i)+\mathbf{v}_j(k). \quad (2)$$

Recall from Fig. 2 that the relay r_j needs to decode the packet $\mathbf{u}(k-j+1)$ during slot k. This means that it needs to detect the signal $\mathbf{u}_{j-1}(k-j+1)$ from (2). Treating all the other signal contents as interference, the signal-to-interference-plus-noise ratio (SINR) for the relay r_j to detect $\mathbf{u}_{j-1}(k-j+1)$ in slot k is

$$\gamma_j(k)=\frac{P_{r_{j-1}}G_{r_{j-1},r_j}}{\sum_{i=0}^{j-2}P_{r_i}G_{r_i,r_j}+\sigma_j^2}. \quad (3)$$

The achievable data rate is $\log_2[1+\gamma_j(k)]$.

In (3), we see that there is no interference coming from the relays in r_j's following hops in the multi-hop path. But the relay r_j's rate is still impacted by the mutual interference coming from all the relays in its preceding hops.

The key point for mitigating such mutual interference so as to realize complete mutual interference immunity is to exploit the fact that the packet $\mathbf{u}(k-j+1)$ is not only contained in signal $\mathbf{u}_{j-1}(k-j+1)$. This packet has in fact been re-encoded into signals $\mathbf{u}_i(k-j+1)$ and transmitted in slots $k-j+1+i$ by the preceding relays r_i, respectively, for all $0\le i\le j-1$. Therefore, as shown in Fig. 3, to decode the packet $\mathbf{u}(k-j+1)$ in slot k, the optimal way for the relay r_j is to store and exploit all the j signals $\mathbf{x}_j(k-j+1+i)$ received during the past j slots $k-j+1+i$, $0\le i\le j-1$, by a successive interference cancellation (SIC) procedure.

Specifically, before decoding the packet $\mathbf{u}(k-j+1)$ in slot k, the relay r_j has already decoded all packets $\mathbf{u}(t)$, $t\le k-j$. Subtracting signals related to these known packets, the signal received in slot $k-j+1+i$ is reduced to

$$\begin{aligned}\tilde{\mathbf{x}}_j(k-j+1+i)=&\sum_{\ell=0}^{i}\sqrt{P_{r_\ell}G_{r_\ell,r_j}}e^{\jmath\theta_{r_\ell,r_j}}\mathbf{u}_\ell(k-j+1+i-\ell)\\&+\mathbf{v}_j(k-j+1+i), \qquad 0\le i\le j-1. \quad (4)\end{aligned}$$

For each i of (4), the relay r_j can detect the signal $\mathbf{u}_i(k-j+1)$, which is transmitted by the preceding relay r_i in slot $k-j+1+i$, with SINR

$$\gamma_j(k-j+1+i)=\frac{P_{r_i}G_{r_i,r_j}}{\sum_{\ell=0}^{i-1}P_{r_\ell}G_{r_\ell,r_j}+\sigma_j^2}. \quad (5)$$

If each relay r_i re-encodes $\mathbf{u}(k-j+1)$ into $\mathbf{u}_i(k-j+1)$ appropriately, the relay r_j can decode a different portion of this packet from each signal $\tilde{\mathbf{x}}_j(k-j+1+i)$. The overall rate of r_j is thus

$$\begin{aligned}R_{r_j}&=\sum_{i=0}^{j-1}\log_2\left[1+\gamma_j(k-j+1+i)\right]\\&=\log_2\left(1+\frac{\sum_{i=0}^{j-1}P_{r_i}G_{r_i,r_j}}{\sigma_j^2}\right). \quad (6)\end{aligned}$$

After decoding the packet $\mathbf{u}(k-j+1)$, the relay r_j can subtract it from all its received signals (4) to prepare for the decoding of the next packet in the next slot. This SIC procedure is repeated by all relays in all slots.

The most interesting result is that there is no mutual interference left in the rate (6). The rate of the relay r_j is not affected by any mutual interference. In other words, multi-hop relaying becomes immune to mutual interference. What's more, each relay can still collect the broadcasting advantage of all the relays in its preceding hops. This means a nice and surprising property: Enjoy benefits of wireless broadcasting without suffering from mutual interference.

The source-destination transmission rate of the multi-hop path can be defined as

$$R=\min_{1\le j\le h+1}R_{r_j}. \quad (7)$$

From (6) and (7), the problem of hop count determination, relay node selection, and rate optimization can be formulated as the following max-min optimization

$$R=\max_{\substack{0\le h\le N\\ r_\ell\in\mathcal{N},1\le\ell\le h}}\ \min_{1\le j\le h+1}\log_2\left(1+\frac{\sum_{i=0}^{j-1}P_{r_i}G_{r_i,r_j}}{\sigma_j^2}\right) \quad (8)$$

under node power constraint $0\le P_j\le P_j^{\max}$, $0\le j\le N$.

IV. Optimal Multi-Hop Relay Selection

To solve (8), exhaustive search over all possible h and relay combinations has computationally prohibitive exponential complexity. Optimal power control only makes it more challenging. Fortunately, the absence of mutual interference in (8) allows us to develop more efficient algorithms. First, because the rate R increases monotonically with relaying powers, each relay simply transmits at full power, i.e.,

$$P_{r_i}=P_{r_i}^{\max}. \quad (9)$$

Moreover, a relay is not affected by the relays in its following hops. Instead, it increases their rates. Therefore, we can adopt an simple greedy strategy to select all the nodes with sufficiently large rates as relays, as outlined in the following algorithm.

Algorithm 1: Optimal Multi-hop Relay Selection
initialize: $r_0 = 0$, $\mathcal{N} = \{1, \cdots, N+1\}$ for iteration $j = 1, 2, \cdots, N$, do
1) Update rates R_i for all remaining nodes $i \in \mathcal{N}$. 2) Select relay $r_j = \arg\max_{i\in\mathcal{N}} R_i$ for hop j. 3) Update node set $\mathcal{N} := \mathcal{N} \setminus \{r_j\}$. 4) Update current multi-hop rate $R = \min_{1\le\ell\le j} R_{r_\ell}$. 5) If $r_j = N+1$, then $h = j-1$, $R = \min\{R, R_{r_j}\}$, stop. 6) If $R \le R_{N+1}$, then $h = j$, $r_{h+1} = N+1$, stop.
output: h, R, r_j, $j = 1, \cdots, h$.

The algorithm begins with $r_0 = 0$. In each iteration j, we select, from all the remaining $N-j+2$ candidate nodes (include the destination node), a node with the highest rate as the relay r_j in hop j. Rates of the remaining candidate nodes are updated (calculated) based on (6) and relays selected for hops 1 to $j-1$. The algorithm stops with the optimal hop count h, the selected relays r_j, $1 \le j \le h$, and the achieved maximum decode-and-forward rate R.

Proposition 1. Algorithm 1 finds the optimal hop count h and selects relays r_j to achieve maximum transmission rate R with computational complexity $O(N^2)$.

Proof: Without loss of generality, let us consider the iteration j. The current multi-hop rate from the source node to the relay r_{j-1} can be written as

$$R^{(j-1)} = \min_{1\le\ell\le j-1} R_{r_\ell} = \min_{1\le\ell\le j-1} \log_2\left[1 + \frac{1}{\sigma_\ell^2}\sum_{i=0}^{\ell-1} P_{r_i} G_{r_i,r_\ell}\right]. \tag{10}$$

We need to select a relay r_j from the rest $(N+1)-(j-1) = N-j+2$ nodes. In Step (1), we first update their rates $R_i^{(j)}$, which can be calculated according to (6). Then, we select the node with the maximum rate in Step (2). Specifically, if the node r_j has the maximum rate, then it should become the relay node in the hop j because

$$R^{(j)} = \min\{R^{(j-1)}, R_{r_j}^{(j)}\} \ge \min\{R^{(j-1)}, R_i^{(j)}\}, \ \forall\ i \ne r_j, i \in \mathcal{N}. \tag{11}$$

Equation (11) remains true for arbitrary relay selection patterns in subsequent iterations thanks to the mutual interference immunity phenomenon. Importantly, this selection is optimal for arbitrary relay selection patterns in subsequent iterations as well. Specifically, let this node be k. Comparing any case that does not select k as relay in hop j with the case that selects k, we can easily show that the former case has no larger rates. This is true for any relay selection pattern that k is not selected as relay in any subsequence hops. For the patterns that select k as a relay in a subsequent hop $q > j$, we can achieve higher or equal multi-hop rates by moving k forward to relay r_j, because such move increases rates of all the relays r_ℓ, $\ell \ge j$, $\ell \ne q$.

If $r_j = N+1$ or $R^{(j)} \le R_{N+1}^{(j)}$, then no extra hop can further increase the multi-hop transmission rate R. Therefore, the algorithm stops in steps (5) and (6).

As to computational complexity, in the worst case the algorithm runs N iterations. In each iteration j, it updates $N-j+2$ rates. Therefore, it calculates a total of $\sum_{j=1}^{N}(N-j+2) = (N^2+3N)/2$ rates R_i. Each rate R_i can be updated iteratively, with the addition of one relay channel coefficient in each iteration. Therefore, the overall computational complexity of the algorithm is $O(N^2)$. $\square$

This wireless algorithm is essentially similar to the well-known Dijkstra's algorithm. The major difference lies in history dependence. In our case, node rates are not fixed. But rather, they are changed by each new relay selected during each iteration.

Similar to Dijkstra's algorithm, the Algorithm 1 can be revised to find the optimal multi-hop paths from the source node 0 to all other network nodes $j = 1, \cdots, N+1$ simultaneously. In this case, there is no fixed destination node, so the stop conditions in Steps (5) and (6) should be revised to

5) Save rate R and relays r_ℓ, $1 \le \ell \le j-1$, as the maximum multi-hop rate and relays for node r_j.
6) For any node $i \in \mathcal{N}$, if $R \le R_i$, then save rate R and relays r_ℓ, $1 \le \ell \le j$, as the maximum multi-hop rate and relays for the node i.

Interestingly, the overall complexity of the revised algorithm is still $O(N^2)$. The optimal multi-hop chains share the same structure for all destination nodes.

Proposition 2. For the 3-node relay network, i.e., $N = 1$, Algorithm 1 achieves the optimal decode-and-forward rate

$$R = \max\left\{\log_2\left(1+\frac{P_0G_{02}}{\sigma_2^2}\right), \min\left[\log_2\left(1+\frac{P_0G_{01}}{\sigma_1^2}\right), \log_2\left(1+\frac{P_0G_{02}+P_1G_{12}}{\sigma_2^2}\right)\right]\right\}. \tag{12}$$

Proof. It is easy to verify (12) following the steps of Algorithm 1. From [7], the rate (12) is the optimal decode-and-forward rate for single-relay Gaussian network. $\square$

We have assumed to adopt a single relay only in each hop. However, the following proposition shows that it does not help to exploit multiple relays in each hop.

Proposition 3. Applying multiple decode-and-forward relays for simultaneous cooperative transmissions in each hop has no better rate than R of (8) which is achieved by using a single relay in each hop.

Proof. If there are multiple relays $R_{j,\ell}$, $\ell = 1, 2, \cdots$, in a hop j, we can divide this hop into two hops j_1 and j_2, where $j_2 = j_1 + 1$. Then we choose the node in $R_{j,\ell}$ with the maximum rate as the relay in the hop j_1, and the rest nodes as relays in j_2. This will increase the multi-hop transmission rate, or at least keep it the same. Repeating this procedure, we can see that the single-relay assumption is optimal. $\square$

V. Simulations

We first simulated a wireless network whose nodes were placed randomly within a square of 1000×1000 square meters. We considered two scenarios: **Rand**, where the source and destination nodes were selected randomly, and **Fixed**, where the source node was placed in the original point and the destination node was placed in the position (1000,1000). The instantaneous channel gain between any pair of nodes with distance d_{ij} was $G_{i,j} = K d_{ij}^{-\alpha}$ with path loss exponent $\alpha = 3$. We normalized all other parameters and transmission powers so that a transmission distance of 1000 meters had a signal-to-noise ratio (SNR) -10 dB.

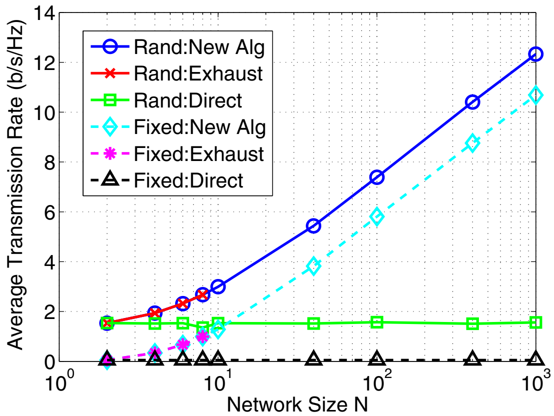

Fig. 4. Average multi-hop transmission rate R as function of network size N for random wireless networks.

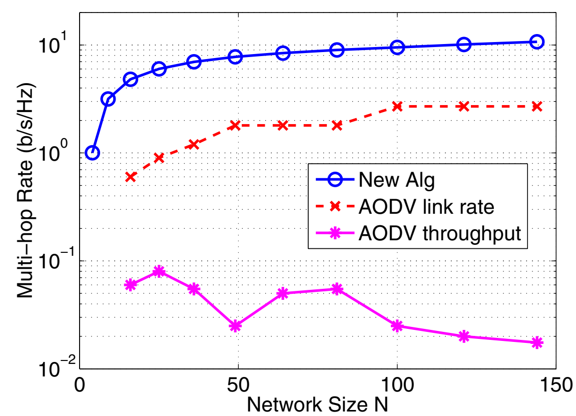

Fig. 5. Multi-hop transmission rate R as function of network size N for grid wireless networks with increasing node density in a fixed area.

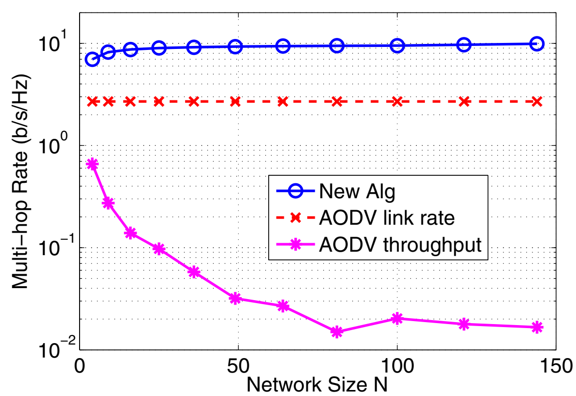

Fig. 6. Multi-hop transmission rate R as function of network size N for grid wireless networks with fixed node density and fixed adjacent node distance of 100 meters.

For each network size N, we generated 1000 to $10,000$ random networks, ran our algorithm in each of them, and calculated the average multi-hop rate. We denoted the result of our algorithm by "**New Alg**". For comparison, we also calculated the direct (no relay) transmission rates (denoted as "**Direct**"), and the rates of the brute-force exhaustive search method (denoted as "**Exhaust**"). Note that the exhaustive search method worked for small network size N only due to its exponential complexity.

Simulation results in Fig. 4 clearly show that the proposed algorithm gave the same result as the exhaustive search method. This demonstrated that our proposed algorithm was optimal. The proposed algorithm worked efficiently for wireless networks with arbitrary size N, even extremely large sizes. In addition, we can see that the average multi-hop transmission rate of random wireless networks had a logarithm increase with network size, i.e., $\log(N)$, for large enough N. This fits well with the capacity scaling law [10]. Nevertheless, if N is not very large, it shows near linear increase.

Next, we compared the theoretical decode-and-forward rate R in (8), achieved by our proposed mutual interference immune techniques, with the multi-hop transmission rate achieved by practical routing algorithms in practical WiFi networks. We simulated fixed grid wireless networks where wireless nodes were placed evenly on a $\sqrt{N} \times \sqrt{N}$ square grid. Two network settings were simulated: (1) Minimum grid distance shrinked with N for increased node density in a fixed network area of 1000×1000 square meters, and (2), minimum grid distance remained constant at 100 meters for fixed node density. We used *NS-3* to simulate the Ad-hoc On-demand Distance Vector (**AODV**) routing algorithm [13] over WiFi IEEE802.11a Physical- and MAC-layer standard [14]. The maximum transmission rate of WiFi varied from 6 Mbps to 54 Mbps with 20 MHz channel bandwidth. We adjusted transmission power so that the SNR of 1000 meter direction transmission is 0 dB. Simulation results are shown in Fig. 5 for network setting (1) and in Fig. 6 for network setting (2).

Simulations show that the practical (AODV) throughput was a tiny fraction of the theoretical decode-and-forward transmission rate only. This is mainly because practice wireless relays have to share the spectrum in a time-division manner. Therefore, the practical throughput reduces exponentially with the number of hops [14]. On the other hand, the ideal (AODV) link rate was somewhat closer to the theoretical decode-and-forward transmission rate. The ideal link rate was defined as the bottle-neck link's transmission rate without considering spectrum sharing and overhead issues. For example, in Fig. 6, ideal link rate 54 Mbps for WiFi standard was achieved because the hop distance was about 100 meters only. Simulation results in Figs. 5 and 6 indicate that if the relays can exploit the interference-immune techniques proposed in this paper to realize full spatial reuse, there is a large room for enhancing multi-hop transmission throughput.

VI. Conclusions

In this paper we first show that full-duplex decode-and-forward relaying with successive interference cancellation can make multi-hop relaying not affected by the mutual interference among the relays. Based on this mutual interference immune phenomenon, we develop an efficient algorithm to find the optimal hop count and select relays to maximize multi-hop transmission rate. The new algorithm is similar to Dijkstra's algorithm. It is efficient and helpful for exploring arbitrarily large wireless networks. Simulation are conducted to verify its efficiency and optimal performance.

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