JOINT RE-ENCODING AND SUCCESSIVE INTERFERENCE CANCELLATION FOR MULTI-HOP RELAY NETWORKS

Xiaohua Li and Jeong Kyun Lee

Department of Electrical and Computer Engineering
State University of New York at Binghamton
Binghamton, NY 13902
Email: {xli,jlee54}@binghamton.edu

ABSTRACT

In this paper, for single-source wireless ad hoc networks, we develop a joint re-encoding and successive interference cancellation (SIC) scheme to realize interference-immune multi-hop relaying. Interference immunity means that the transmission rate is not affected by the mutual interference among the relays. This leads to a greedy near-optimal algorithm that is similar to the Dijkstra's algorithm for wireless relay selection and multi-hop routing. To evaluate the practical performance of this scheme, we analyze quantitatively the performance of SIC under channel model errors and channel estimation errors. The vital role of the relative signal strength and the training sequence length is determined. Simulations are conducted to demonstrate that the proposed scheme maximizes transmission rate and reduces scheduling overhead drastically.

***Index Terms*—** successive interference cancellation, multi-hop relay, wireless networks, signal to noise ratio, cross-layer design

1. INTRODUCTION

For wireless ad-hoc networks consisting of an arbitrary number of wireless nodes, a basic routing problem, i.e., selecting relays to construct multi-hop relaying paths to maximize source-destination transmission rates, is a long-standing open problem. In wired networks, sophisticated algorithms such as Dijkstra's algorithm can be used to solve this basic multi-hop routing problem [1]. In wireless networks, however, this problem is difficult because of the mutual interference among the relays.

This optimal multi-hop routing problem was studied in [2] but for a linear wireless network only. For the general Gaussian ad-hoc networks, the optimal multi-hop rate with decode-and-forward relays was given in [3] [4], where it was shown that the rate is not affected by the mutual interference. Nevertheless, the routing problem, i.e., optimal relay selection and multi-hop path construction, was still a challenge. Under a different model, in [5][6] we gave the optimal decode-and-forward rate and, more importantly, developed an efficient algorithm to select relays and to construct the optimal multi-hop paths from a source node to all destination nodes.

So far the optimal multi-hop rates were derived with the ideal asymptotic equipartition property (AEP), where random codes with infinite length, full-duplex relaying, and perfect successive interference cancellation (SIC) were used. In this paper we address this problem under more realistic assumptions. Specifically, we consider half-duplex decode-and-forward relays. In addition, we propose a practical joint re-encoding and SIC scheme to realize the interference-immune multi-hop relaying. We also analyze the performance of SIC under practical constraints.

Currently, there is a great interest for the upper-layer protocols to apply SIC for interference mitigation [7]. Thus, it is important to analyze the performance of SIC in practice. The results of this paper can play an important role. A significant drawback of existing upper-layer studies such as [7]-[9] is that they can only take some limited benefits of SIC. In contrast, in this paper we show that by applying appropriate re-encoding with the SIC, more benefits can be achieved. In addition, by simulations we show that the proposed scheme can potentially reduce drastically the overhead of upper-layer protocols.

The organization of this paper is as follows. In Section 2, we give the multi-hop wireless network model. In Section 3, we develop the joint re-encoding and SIC scheme and analyze the SIC performance. Simulations are conducted in Section 4, and conclusions are presented in Section 5.

2. MULTI-HOP WIRELESS NETWORK MODEL

In a wireless network with $N+2$ nodes, we need to construct multi-hop transmission paths from a source node to multiple destination nodes. The multi-hop routing problem is to determine the optimal number of hops (hop count), to select a relay for each hop, and to determine the relay's transmission power so as to maximize source-destination transmission rate.

Consider the single-source single-destination case first. Denote the source node as node 0, the destination node as node $N+1$, and all the N candidate relay nodes as the set $\mathcal{N} = \{1, 2, \cdots, N\}$. Let the hop count be $h+1$, where $0 \leq h \leq N$, and the relay node in hop i be $r_i \in \mathcal{N}$. We define $r_0 \stackrel{\triangle}{=} 0$ and $r_{h+1} \stackrel{\triangle}{=} N+1$.

With the half-duplex decode-and-forward relaying strategy, we adopt a slotted multi-hop packet forwarding scheme, where even-numbered relays transmit in even-numbered slots, and odd-numbered relays transmit in odd-numbered slots. Define $Q = \lfloor \frac{h}{2} \rfloor$, where $\lfloor x \rfloor$ is the maximum integer not larger than x. As shown in Fig. 1, during the even-numbered slot $2k$, $k = 0, 1, \cdots$, each even-numbered relay r_{2q}, $q = 0, 1, \cdots, Q$, re-encodes a packet $\mathbf{u}(k-q)$ into a signal $\mathbf{u}[r_{2q}, k-q]$, and transmits this signal. Meanwhile, each odd-numbered relay r_{2q+1} receives (and decodes) a packet $\mathbf{u}(k-q)$, where $q = 0, 1, \cdots, Q_o$, and

$$Q_o = \begin{cases} Q, & \text{if } h \text{ is odd;} \\ Q-1, & \text{if } h \text{ is even.} \end{cases} \tag{1}$$

The transmission-receiving schedule in odd-numbered slots can be defined similarly. The destination node r_{h+1} receives signals in both even-numbered and odd-numbered slots.

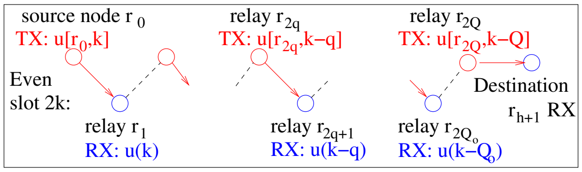

Fig. 1. Multi-hop transmission and receiving schedule in an even-numbered slot $2k$ for an even hop count h.

During the even-numbered slot $2k$, the signal received by the relay r_{2q+1}, $0 \leq q \leq Q_o$, is

$$\mathbf{x}[r_{2q+1}, 2k] = \sum_{i=0}^{Q} \sqrt{P(r_{2i})G(r_{2i}, r_{2q+1})} e^{j\theta(r_{2i}, r_{2q+1})} \times \mathbf{u}[r_{2i}, k-i] + \mathbf{v}[r_{2q+1}, 2k], \quad (2)$$

where $P(r_{2i})$ is the transmission power of the relay r_{2i}, $j = \sqrt{-1}$, $\sqrt{G(r_{2i}, r_{2q+1})} e^{j\theta(r_{2i}, r_{2q+1})}$ is the instantaneous propagation channel, and $\mathbf{v}[r_{2q+1}, 2k]$ is additive white Gaussian noise (AWGN). Note that $\mathbf{x}[r_{2q+1}, 2k]$, $\mathbf{u}[r_{2i}, k]$ and $\mathbf{v}[r_{2q+1}, 2k]$ are vectors containing all the samples in the slot $2k$.

Similarly, during the odd-numbered slot $2k + 1$, the relay r_{2q}, $0 \leq q \leq Q$, receives signal

$$\mathbf{x}[r_{2q}, 2k+1] = \sum_{i=0}^{Q_o} \sqrt{P(r_{2i+1})G(r_{2i+1}, r_{2q})} e^{j\theta(r_{2i+1}, r_{2q})} \times \mathbf{u}[r_{2i+1}, k-i] + \mathbf{v}[r_{2q}, 2k+1]. \quad (3)$$

We assume complex flat fading channels with gain $G(i, j)$ from node i to node j, zero-mean AWGN with power $\sigma^2(i)$ for node i in all slots, and individual relay power limit $0 \leq P(i) \leq P^{\max}(i)$. All re-encoded signals $\mathbf{u}[i, t]$ have unit power. We also assume that all channel coefficients and re-encoding rules are public knowledge. Note that for the general frequency selective fading channels, we can apply OFDM signaling to convert them into flat fading channels.

3. MULTI-HOP RELAY OPERATION AND OPTIMIZATION

3.1. Joint re-encoding and SIC for relay signal processing

Let us consider first the odd-numbered relay r_{2q+1} which has received signal (2). Because this relay has full knowledge of all the packets transmitted by the relays in its subsequent hops, it can subtract signals $\mathbf{u}[r_{2i}, k-i]$, $i = q+1, \cdots, Q$, from (2). Then it proceeds to decode the packet $\mathbf{u}(k-q)$ during the slot $2k$.

Proposition 1. The maximum decode-and-forward rate of the relay r_{2q+1}, $0 \leq q \leq Q_o$, is

$$R(r_{2q+1}) = \frac{1}{2} \log_2 \left(1 + \frac{\sum_{i=0}^{q} P(r_{2i})G(r_{2i}, r_{2q+1})}{\sigma^2(r_{2q+1})} \right). \quad (4)$$

Proof. The proof follows [3] based on AEP and random codes. In our case the relays can not conduct coherent transmit beamforming, which is more practical for ad hoc networks. In addition, we has half-duplex relaying and thus the parameter $1/2$. □

Similarly, the maximum rate of the even-numbered relay r_{2q}, $0 \leq q \leq Q$, is

$$R(r_{2q}) = \frac{1}{2} \log_2 \left(1 + \frac{\sum_{i=0}^{q-1} P(r_{2i+1})G(r_{2i+1}, r_{2q})}{\sigma^2(r_{2q})} \right). \quad (5)$$

The maximum rate of the destination node $r_{h+1} = N + 1$ is

$$R(r_{h+1}) = \frac{1}{2} \log_2 \left(1 + \frac{\sum_{i=0}^{Q} P(r_{2i})G(r_{2i}, r_{h+1})}{\sigma^2(r_{h+1})} \right) + \frac{1}{2} \log_2 \left(1 + \frac{\sum_{i=0}^{Q_o} P(r_{2i+1})G(r_{2i+1}, r_{h+1})}{\sigma^2(r_{h+1})} \right). \quad (6)$$

From (4)-(6), the most interesting observation is that there is no mutual interference left in the rate expressions of the relays. In other words, multi-hop relaying becomes immune to mutual interference. What's more, each relay can collect the transmission power of all the even- or odd- numbered transmitting relays in its preceding hops. This means a nice and surprising property: Enjoy benefits of wireless broadcasting without suffering from interference.

In this paper we focus on developing a practical joint re-encoding and SIC scheme for the relays to achieve closely the maximum rates (4)-(6). This scheme exploits the characteristics of multi-hop relaying, i.e., a packet is transmitted repeatedly by multiple nodes in multiple slots. With appropriate re-encoding techniques, mutual interference in the received signals (2)-(3) can be compensated for successfully.

Without loss of generality, consider the case that the relay r_{2q+1} decodes the packet $\mathbf{u}(k-q)$ in the slot $2k$. The packet $\mathbf{u}(k-q)$ is transmitted not only by the one-hop ahead relay r_{2q} (re-encoded to signal $\mathbf{u}[r_{2q}, k-q]$ in slot $2k$) but also by all preceding even-numbered relays r_{2i} (re-encoded to signal $\mathbf{u}[r_{2i}, k-q]$ in slot $2(k-q+i)$), where $0 \leq i \leq q$. The optimal way for the relay r_{2q+1} is to store and exploit all the signals $\mathbf{x}[r_{2q+1}, 2(k-q+i)]$ received in the past q even-numbered slots $2(k-q+i)$, $0 \leq i \leq q$.

Specifically, before decoding the packet $\mathbf{u}(k-q)$ in slot $2k$, the relay r_{2q+1} has already decoded and transmitted all packets $\mathbf{u}(t)$, $t \leq k-q$. Subtracting signals related to these known packets from (2), the signal received in slot $2(k-q+i)$ is reduced to

$$\tilde{\mathbf{x}}[r_{2q+1}, 2(k-q+i)] = \sum_{\ell=0}^{i} \sqrt{P(r_{2\ell})G(r_{2\ell}, r_{2q+1})} e^{j\theta(r_{2\ell}, r_{2q+1})} \times \mathbf{u}[r_{2\ell}, k-q+i-\ell] + \mathbf{v}[r_{2q+1}, 2(k-q+i)]. \quad (7)$$

Based on (7), for each i, the relay r_{2q+1} can detect a signal $\mathbf{u}[r_{2i}, k-q]$, which is re-encoded from the packet $\mathbf{u}(k-q)$ by r_{2i}. The signal to interference and noise ratio (SINR) for this signal detection is

$$\Gamma(r_{2q+1}, r_{2i}) = \frac{P(r_{2i})G(r_{2i}, r_{2q+1})}{\sum_{\ell=0}^{i-1} P(r_{2\ell})G(r_{2\ell}, r_{2q+1}) + \sigma^2(r_{2q+1})}. \quad (8)$$

Obviously, only a portion of the packet $\mathbf{u}(k-q)$ is decoded in (8).

If each relay r_{2i} re-encodes $\mathbf{u}(k-q)$ into $\mathbf{u}[r_{2i}, k-q]$ appropriately so that the relay r_{2q+1} decodes a different portion of this packet from each signal $\tilde{\mathbf{x}}[r_{2q+1}, 2(k-q+i)]$, the optimal rate for the relay r_{2q+1} is

$$R(r_{2q+1}) = \frac{1}{2} \sum_{i=0}^{q} \log_2 \left(1 + \Gamma(r_{2q+1}, r_{2i})\right). \quad (9)$$

We can show that (9) is equal to (4).

It is non-trivial for all the even-numbered relays r_{2i} to re-encode the packet $\mathbf{u}(k-q)$ so that all odd-numbered relays r_{2q+1} can achieve the maximum rates (4). Each even-numbered relay r_{2i} needs to transmit a portion of its data to each odd-numbered relay r_{2q+1}. Denote the rate of this portion of data as $R(r_{2q+1}, r_{2i})$. Then

$$R(r_{2q+1}, r_{2i}) \leq \frac{1}{2}\log_2\left(1 + \Gamma(r_{2q+1}, r_{2i})\right). \quad (10)$$

Since a relay's transmitted data is limited by its receiving rate, we have

$$R(r_{2q+1}, r_{2i}) \leq R(r_{2i}). \quad (11)$$

In addition, the sum of all rate portions received by a relay should be no less than this relay's rate. Therefore, we have

$$\begin{bmatrix} R(r_1, r_0) & & \\ \vdots & \ddots & \\ R(r_{2Q_o+1}, r_0) & \cdots & R(r_{2Q_o+1}, r_{2Q_o}) \end{bmatrix} \mathbf{1} \geq \mathbf{R}_o, \quad (12)$$

where $\mathbf{R}_o = [R(r_1), R(r_3), \cdots, R(r_{2Q_o+1})]^T$ is a vector of all the odd-numbered relay rates, and $\mathbf{1}$ is a $(Q_o + 1) \times 1$ vector with all elements being 1. From (10)-(12), we can determine each $R(r_{2q+1}, r_{2i})$.

The challenge comes from the fact the data bits received by all the odd-number relays from a common even-numbered relay form a subset chain. To resolve this, we use the following re-encoding procedure. Let $\mathbf{b} = [b_1, \cdots, b_M]$ denote the symbols of a packet. The relay r_{2i} re-encodes $\mathbf{b}$ into $[c_1^{2i}, \cdots, c_M^{2i}] = \mathbf{b}\mathbf{E}_{2i}$, where $\mathbf{E}_{2i}$ is an $M \times M$ full-rank re-encoding matrix for the relay r_{2i}. Then the first ℓ symbols $\mathbf{c}_\ell^{2i} = [c_1^{2i}, \cdots, c_\ell^{2i}]$, where $\ell/M \geq R(r_{2q+1}, r_{2i})/R(r_{2i})$, are assigned with appropriate transmission power so that the SINR $\Gamma(r_{2q+1}, r_{2i})$ can be satisfied. This way, the relay r_{2q+1} can receive successfully $\mathbf{c}_\ell^{2i}$. With all such symbols received from the even-numbered relays, the relay r_{2q+1} can decode the packet $\mathbf{b}$ by solving the equation

$$[\mathbf{c}_\ell^0, \cdots, \mathbf{c}_\ell^{2q}] = \mathbf{b}\mathbf{D}_{2q+1}, \quad (13)$$

where $\mathbf{D}_{2q+1}$ consists of the corresponding columns of all the re-encoding matrices $\mathbf{E}_{2i}$ and has full row rank with probability 1.

3.2. Performance of SIC under practical constraints

So far we have assumed perfect SIC. In practice, SIC is limited by various practical constraints. One of them is the finite resolution of quantization. From [10], quantization signal to noise ratio (SNR) can be described as $\gamma_Q = 10^{0.602b+1.079}$, where b is the number of bits each sample is quantized to. If the continuous-time signal has SNR γ, then the digital signal after quantization has SNR

$$\hat{\gamma} = \frac{1}{\frac{1}{\gamma} + \left(1 + \frac{1}{\gamma}\right)\frac{1}{\gamma_Q}}. \quad (14)$$

In Fig. 2(a), we show the SNR of the quantized signal versus the SNR of the original continuous-time signal. For half-duplex relays, since the SNR of the received signal (2) is usually less than 100 dB, a practical A/D with $b \geq 14$ should be enough. In contrast, for full-duplex relays, the self-interference can be too strong. Fortunately, techniques such as antenna separation and analog interference cancellation are commonly adopted to reduce self-interference before quantization [11].

The next practical constraint is the channel model error, which is due to the linear finite impulse response (FIR) channel model of the real channel. Assume the envelope of the power spectral density of the real channel attenuates exponentially as $f(\tau) = Ae^{-\frac{\tau}{\lambda}}$, where the constant λ can be determined by the maximum excess delay $\tau_{\max}$

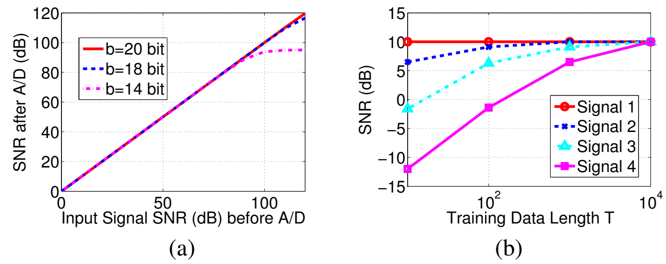

Fig. 2. (a) Effect of finite resolution quantization. (b) Effect of imperfect SIC.

or channel length. The signal power covered in the channel model is $\int_0^{\tau_{\max}} f(\tau)d\tau$, while the signal power not covered is $\int_{\tau_{\max}}^{\infty} f(\tau)d\tau$ which is the power of the channel model error.

We can use a factor $\beta_{r_{2i},r_{2q+1}}$ to describe the channel model error between the relays r_{2i} and r_{2q+1}. The power of the channel model error is $\beta_{r_{2i},r_{2q+1}}|h_{r_{2i},r_{2q+1}}|^2$, where the channel is $h_{r_{2i},r_{2q+1}} = \sqrt{P(r_{2i})G(r_{2i}, r_{2q+1})}e^{j\theta(r_{2i},r_{2q+1})}$. The actual signal power from the relay r_{2i} to the relay r_{2q+1} is $(1 + \beta_{r_{2i},r_{2q+1}})|h_{r_{2i},r_{2q+1}}|^2$. Even if just considering the channel model error, the signal's SNR is $1/\beta_{r_{2i},r_{2q+1}}$ only. More specifically, if $\tau_{\max}$ is defined as η dB below the peak power level [12], then it can be shown that the SNR is $1/\beta_{r_{2i},r_{2q+1}} = \eta$ (dB) only.

This has a very severe consequence: the more powerful a signal component is, the more residue error it introduces to other signals in SIC. Obviously, for full-duplex relays, this problem is even more severe considering the strong self-interference.

The third practical constraint is the channel estimation error. The accuracy of channel estimation depends on training sequence length T. Even though there are various blind or semi-blind channel estimation methods, their performance is secondary to the training method. Considering the signal model (2), the maximum-likelihood channel estimator is

$$\hat{h}_{r_{2i},r_{2q+1}} = \left(\sum_{n=1}^{T}|u[r_{2i}, n]|^2\right)^{-1}\sum_{n=1}^{T}x[r_{2q+1}, n]u^*[r_{2i}, n], \quad (15)$$

where $u[r_{2i}, n]$ and $x[r_{2q+1}, n]$ are training symbols and received samples at time n, respectively.

Proposition 2. Applying channel estimation (15) in SIC, the SNR of the $(q-i)$th stage signal detection in (2) is

$$\hat{\Gamma}(r_{2q+1}, r_{2i}) = \frac{|h_{r_{2i},r_{2q+1}}|^2}{\sigma_a^2(r_{2q+1}, r_{2i})}, \qquad i = q, q-1, \cdots, 0, \quad (16)$$

where

$$\sigma_a^2(r_{2q+1}, r_{2i}) = \sum_{\ell=0}^{i-1}(1 + \beta_{r_{2\ell},r_{2q+1}})|h_{r_{2\ell},r_{2q+1}}|^2 + \sigma^2(r_{2q+1}) + \beta_{r_{2i},r_{2q+1}}|h_{r_{2i},r_{2q+1}}|^2 + \sum_{\ell=i+1}^{q}\frac{1}{T}\sigma_a^2(r_{2q+1}, r_{2\ell}) \quad (17)$$

is the sum power of the mutual interference, the noise, and the accumulated SIC residue errors.

Proof. According to [13], the Cramer-Rao lower bound of the channel estimator (15) is

$$E\left[|\hat{h}_{r_{2i},r_{2q+1}} - h_{r_{2i},r_{2q+1}}|^2\right] = \frac{1}{T}\sigma_a^2(r_{2q+1}, r_{2i}). \quad (18)$$

Note that $\sigma_a^2(r_{2q+1}, r_{2i})$ includes residue errors of all previous SIC stages. From (2), this stage of SIC leaves residue error $(h_{r_{2i},r_{2q+1}} - \hat{h}_{r_{2i},r_{2q+1}})\mathbf{u}[r_{2i}, k-i]$. Together with the residue errors of previous stages and the remaining signal components, we can derive (16) and (17). □

From (17), we can see that a long training sequence length T is helpful to mitigate the accumulation of SIC residue errors. If $T \to \infty$, then there is not error accumulation, and the channel model error and the mutual interference play major roles. One way to reduce the channel model error is to let the training sequence of each relay be the only transmission for some time. But this will reduce T.

An example is shown in Fig. 2(b), where we need to use SIC to decode 4 signals, each with an ideal SNR 10 dB. We set $\eta = 30$ dB. We can see that the SIC performance critically depends on T. For small T, the last several stages of SIC are unreliable.

3.3. Efficient algorithm for multi-hop relay selection

The problem of hop count determination, relay node selection, and multi-hop rate optimization can be formulated as max-min optimization

$$R = \max_{\substack{0 \le h \le N \\ r_\ell \in \mathcal{N}, 1 \le \ell \le h}} \min_{1 \le i \le h+1} R(r_i) \tag{19}$$

under node power constraint $0 \le P(i) \le P^{\max}(i), 0 \le i \le N$.

Because rates $R(r_i)$ increase monotonically with relaying powers, each relay should simply transmit at full power, i.e., $P(r_i) = P^{\max}(r_i)$. This resolves the challenging power control issue. In addition, a relay is not affected by the relays in its subsequent hops. It only increases the rates of the relays in its subsequent hops. Therefore, we can try a greedy procedure to select the relays with the largest rates, similarly as the algorithm in [6].

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. The rates are updated according to (4)-(6) and (16). Each node keeps two rates (for even and odd j) updated and stored.

This algorithm has computational complexity $O(N^2)$. It can find multi-hop paths from a source node to all destination nodes simultaneously. Obviously, this wireless algorithm is essentially similar to the well-known Dijkstra's algorithm.

4. SIMULATIONS

First, we simulated a wireless network whose nodes were placed randomly within a square of 1000×1000 meters. We considered two scenarios: **Rand** (source and destination nodes were placed randomly) and **Fixed** (source was in the origin and destination was in the position (1000,1000)). The channel gain between two nodes with distance d_{ij} was $G(i,j) = K d_{ij}^{-3}$. Parameters were normalized so that a transmission distance of 1000 meters had SNR 10 dB.

For each network size N, we generated 1000 random networks, ran our algorithm in each of them, and calculated average multi-hop rate. We denoted the result of our algorithm by "**New Alg**", and compared it with the direct (no relay) transmission result ("**Direct**") and the brute-force exhaustive search result ("**Exhaust**"). Simulation results are shown in Fig. 3, which clearly demonstrates that our proposed algorithm is near optimal.

Next, we compared the rate R achieved by our algorithm with the multi-hop transmission rate achieved by a practical routing

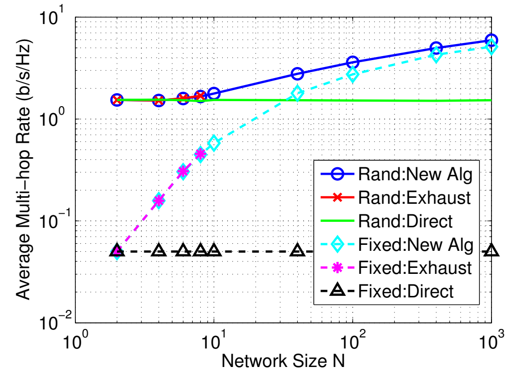

Fig. 3. Average multi-hop transmission rate R of random wireless networks.

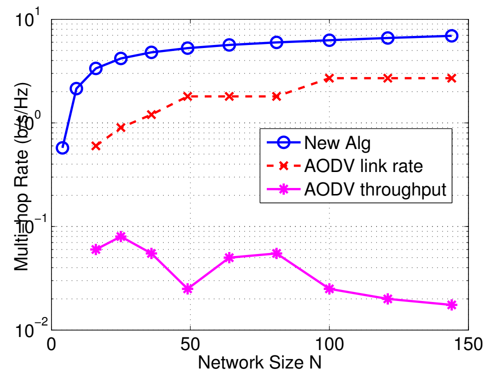

Fig. 4. Multi-hop transmission rate R of fixed grid networks.

algorithm in a practical WiFi network. We simulated fixed grid wireless networks where wireless nodes were placed evenly on a constant square grid. We used *NS-3* to simulate the Ad-hoc On-demand Distance Vector (**AODV**) routing algorithm [14] over WiFi IEEE802.11a Physical- and MAC-layer standard. Simulation results are shown in Fig. 4.

Obviously, practical AODV throughput was just a tiny fraction of R. 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 [15]. On the other hand, the link rate curve indicates that if the relays can exploit the interference-immune techniques proposed in this paper to realize full spatial reuse with low scheduling overhead, there lies great potential for enhancing multi-hop transmission throughput.

5. CONCLUSION

In this paper we develop a joint re-encoding and successive interference cancellation scheme for half-duplex decode-and-forward relays to realize interference immune multi-hop relaying. We also analyze the performance of SIC under practical constraints of finite quantization resolution, finite-length channel model, and finite-training channel estimation.

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