Opportunistic Cooperative Channel Access in Distributed Wireless Networks with Decode-and-Forward Relays

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***Abstract*— This letter studies distributed opportunistic channel access in a contention-based wireless network with decode-and-forward relays. If a source wins a contention, the channel state information in the first-hop channel is estimated, and a decision is made for the winner source to either give up the transmission opportunity and let all sources start a new contention, or transmit to the relay. Once the relay gets the traffic, it may have a sequence of probings of the second-hop channel. The optimal decision strategies for the two hops are derived in this letter. Simulation results show that our scheme is beneficial when second-hop channels have larger average signal-to-noise ratio.**

***Index Terms*— Opportunistic transmission, optimal stopping.**

I. INTRODUCTION

In a distributed wireless network, normally channel contention is adopted, for example, by using handshakes of request-to-send (RTS) and clear-to-send (CTS) before a data transmission. To efficiently utilize the wireless channel, it may be better if a source that wins the channel contention could give up its transmission opportunity when its channel is not good, i.e., it does not transmit upon reception of CTS, and thus, all sources immediately start a new channel contention. This idea is called *distributed opportunistic channel access*. The challenge is: how does distributed opportunistic channel access achieve optimality in terms of maximal system throughput? The challenge was addressed in [1]. A source first sends a probing packet (e.g., RTS) to its destination for channel contention. If the contention is successful, the destination estimates the channel signal-to-noise ratio (SNR) and feedbacks (e.g., by using CTS) to the source. If the channel SNR is less than a threshold value, which can be numerically calculated based on the users' channel statistics, the source gives up its transmission opportunity; otherwise, the source transmits its traffic using the maximal achievable transmission rate of the probed channel. Ref. [2], [3], [4] are follow-ups of [1], considering that channel information is imperfect, multiple transmissions are possible, and there exists a bound on the average interval between two transmissions, respectively. For wireless relaying networks, distributed opportunistic channel access is investigated in [5] and [6] with amplify-and-forward relays and decode-and-forward (DF) relays, respectively. In specific, a distributed DF relaying network is considered in [6], in which each source-destination pair is aided by a DF relay. If a source has traffic to send, it sends a probing packet, and based on reception of the probing packet, the information of the first-hop channel SNR (from the source to its relay and to the destination) is obtained. Then the source decides to 1) give up, or 2) transmit with direct link, or 3) continue to probe the second hop (from the relay to the destination). If the source decides to probe the second hop, the channel SNR of the second hop is estimated, and it is decided either to give up or to transmit (by using the direct link or the relay link, whichever has better utility).

Different from [6], here we propose another method for a distributed DF relaying network. A source also first sends a probing packet, and after the first-hop channel SNR is obtained, we propose that the source either gives up the transmission opportunity or utilizes the first-hop channel first (by transmitting to its relay and letting its relay wait for a good second-hop channel to forward the received traffic, referred to as *relay-waiting*). The rationale for the relay-waiting is: if the first-hop instantaneous SNR is good but the second-hop instantaneous SNR is bad, the relay-waiting can still exploit the good first-hop channel, while the scheme in [6] is very likely to give up, thus wasting the good first-hop channel. In this letter, we derive an optimal strategy for our proposed scheme, and show that our scheme is beneficial when the second-hop channels have larger average SNR.

II. SYSTEM MODEL

Consider a distributed DF relaying network with M source-destination pairs. Each source-destination pair is assigned a relay. First consider the case with direct links from sources to destinations. Similar to [6], to probe the first-hop channels, a source can send a probing packet. If there is no collision, the probing packet is received by both its relay and its destination. By reception of the probing packet, the relay and the destination can estimate the channel SNRs from the source to themselves. Then the relay reports its channel SNR information to the destination, and the destination makes a decision for the first hop (give up or transmit). For this case, by reception of the reporting message from the relay, the destination can actually estimate the channel SNR from the relay to itself, and thus, the destination has complete channel SNR information for the two hops: from the source to the relay, from the source to itself, and from the relay to itself. Then the destination can calculate the achievable end-to-end transmission rate denoted as R between the source and itself. Therefore, although the communication from the source to the destination is with two hops, it can be treated as a virtual one-hop communication with achievable rate R. So the same method as that in [1] (which deals with single-hop networks) can be used to find an optimal opportunistic channel access strategy. Therefore, in this letter, we investigate the case without direct link between any source-destination pair. For source-destination pair i, channels in the first hop (from source i to its relay) and the second hop (from the relay to destination i) follow Rayleigh fading with average received SNR being η_i and ρ_i, respectively.

Similar to [1] [5] [6], the M sources use a channel contention procedure as follows. At a minislot with duration σ,

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each source sends an RTS with probability p to its relay. So at a minislot, if no source transmits, i.e., the minislot is idle (the probability is $(1-p)^M$), then all sources start a new channel contention in the next minislot; if more than one source send RTS (the probability is $1-(1-p)^M - Mp(1-p)^{M-1}$), a collision happens, and thus, all sources start a new channel contention after a time-out duration following the collision; if only one source sends RTS (with probability $Mp(1-p)^{M-1}$), we call the source a *winner source*. Define *an observation* as the interval from the starting point of the channel contention until a winner source appears (i.e., its RTS is successfully received by its relay). The average duration of an observation is $\tau_1 = \frac{(1-p)^M}{Mp(1-p)^{M-1}} \cdot \sigma + \frac{1-(1-p)^M - Mp(1-p)^{M-1}}{Mp(1-p)^{M-1}}(\tau_{RTS} + \tau_{timeout}) + \tau_{RTS}$, in which τ_{RTS} and $\tau_{timeout}$ are RTS and time-out durations, respectively.

At the end of an observation (say, observation n), the winner source's relay can estimate the channel SNR from the winner source to itself by the RTS reception, and it decides from two options: 1) option *give-up*: to give up the transmission opportunity, and notify the source of the decision by sending back a CTS. This CTS is also received by other sources. Thus, subsequently all sources can start a new contention. 2) option *stop*: to *stop* the process and utilize the first-hop transmission opportunity, and send back a CTS to notify the decision. In the CTS, a transmission rate denoted as R_n is also indicated for transmission from the winner source to the relay. Then the winner source transmits for duration of a channel coherence time denoted as τ_d by using transmission rate R_n (the optimal value of R_n is derived in Section IV). The subsequent action of the relay is detailed in Section III.

For observation n, if the winner source stops, denote reward Y_n as the total amount of traffic that is sent by the winner source and received by its destination, and denote T_n as the time duration from observation 1 until observation n plus the time used for transmissions in the two hops. Denote N as the *stopping time*, i.e., the winner sources in the first $N-1$ observations do not stop, and the winner source in the Nth observation stops. This letter targets at an optimal stopping time denoted as N^*, which makes the system achieve the maximal system throughput, i.e.,

$$N^* = \arg\sup_{N\geq 0} \mathbb{E}[Y_N]/\mathbb{E}[T_N] \quad (1)$$

where $\mathbb{E}[\cdot]$ means expectation. N^* is also referred to as *optimal stopping strategy*. Based on [7, Chapter 6], we can transform problem (1) into a problem that maximizes reward $Y_N - \lambda T_N$ with $\lambda > 0$. In specific, for $\lambda > 0$, an optimal strategy denoted as $N^*(\lambda)$ should be found, which maximizes expected reward of the transformed problem:

$$U(\lambda) = \sup_{N(\lambda)\geq 0} \{\mathbb{E}[Y_{N(\lambda)}] - \lambda \mathbb{E}[T_{N(\lambda)}]\}. \quad (2)$$

If we find a λ^* such that $U(\lambda^*) = 0$, an optimal strategy of Problem (1) is given as $N^*(\lambda)$ with $\lambda = \lambda^*$ [7].

From [7], an optimal strategy of Problem (2) exists if the following two conditions are satisfied: $\mathbb{E}\big[\sup_n (Y_n - \lambda T_n)\big] < \infty$; and $\limsup_{n\to\infty}(Y_n - \lambda T_n) = -\infty$ almost surely. From Sections III and IV it can be seen that R_n should be finite (because if $R_n = \infty$, the probability for a relay to have a good enough second-hop channel to forward its received traffic is zero). As $Y_n \leq R_n\tau_d$, the first condition is apparently satisfied. Since $\limsup_{n\to\infty} T_n = \infty$, the second condition is also satisfied. Therefore, an optimal strategy of Problem (2) exists.

An optimal strategy of Problem (2) has two parts: optimal first-hop and second-hop strategies, discussed next.

III. Strategy for the Second Hop

Consider observation n. Here we first try to find an optimal strategy for the second hop, i.e., we assume that the winner source, denoted as $w(n)$, stops and transmits to its relay with rate R_n. For the second hop, the relay should find its best strategy. The relay first sends an RTS to the destination, and the destination estimates the second-hop channel SNR denoted as r_g and feedbacks a CTS that includes the channel SNR information, referred to as a *channel probing*. If the achievable second-hop transmission rate, given as $\log_2(1+r_g)$, is not less than R_n, the relay transmits to the destination by using transmission rate R_n with duration τ_d; otherwise, the relay decides to give up or to continue channel probing. If the relay decides to give up, all sources start a new channel contention. If the relay decides to continue channel probing, the relay waits for channel coherence time τ_d and has a new RTS-CTS exchange with the destination (a new channel probing), and transmits if the achievable second-hop transmission rate is not less than R_n, or decides to give up or to continue channel probing otherwise. This procedure is repeated until the relay transmits or gives up. So there are a sequence of decisions in the second hop, which is challenging. To address this, we take a new viewpoint for second-hop strategies, as follows.

Denote S_l as the second-hop strategy that the relay can have up to l channel probings of its channel to the destination. So if the relay cannot find a second-hop channel realization with achievable rate not less than R_n within l channel probings, the relay is forced to give up. Denote $V^l(\lambda)$ (which is a function of λ) as the net reward of strategy S_l. Therefore, an optimal second-hop strategy should achieve net reward $\max\{\mathbb{E}[V^1(\lambda)], \mathbb{E}[V^2(\lambda)], ..., \mathbb{E}[V^\infty(\lambda)]\}$. We have

$$\begin{aligned}\mathbb{E}[V^l(\lambda)] &= \Pr[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_2) \\ &+ \Pr[r_g^1 < r_n, r_g^2 \geq r_n](R_n\tau_d - 2\lambda\tau_2) + ... \\ &+ \Pr[r_g^1 < r_n, ..., r_g^{l-1} < r_n, r_g^l \geq r_n](R_n\tau_d - l\lambda\tau_2) \\ &+ \Pr[r_g^1 < r_n, ..., r_g^{l-1} < r_n, r_g^l < r_n] \\ &\times(-(l-1)\lambda\tau_2 - \lambda(\tau_{RTS} + \tau_{CTS})) \quad (3)\end{aligned}$$

in which Pr$[\cdot]$ means probability, τ_{CTS} is CTS transmission duration, $\tau_2 = \tau_{RTS} + \tau_{CTS} + \tau_d$ is the time cost for probing and waiting (or transmission) in the second hop, $r_n \triangleq 2^{R_n} - 1$ is the minimum required SNR of the second hop for achievable transmission rate R_n, and $r_g^1, r_g^2, ..., r_g^l$ are channel SNRs of 1st, 2nd, ..., lth channel probing of the relay. We have

$$\begin{aligned}\mathbb{E}[V^\infty(\lambda)] &= \Pr[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_2) \\ &+ \Pr[r_g^1 < r_n, r_g^2 \geq r_n](R_n\tau_d - 2\lambda\tau_2) + ... \\ &+ \Pr[r_g^1 < r_n, ..., r_g^{l-1} < r_n, r_g^l \geq r_n](R_n\tau_d - l\lambda\tau_2) \\ &+ \Pr[r_g^1 < r_n, ..., r_g^{l-1} < r_n, r_g^l < r_n](\mathbb{E}[V^\infty(\lambda)] - l\lambda\tau_2). \quad (4)\end{aligned}$$

Denote $F_{w(n)}(\cdot)$ as the cumulative distribution function of the SNR of the second-hop channel of winner source $w(n)$'s relay. From (3) and (4), we have

$$\mathbb{E}[V^{\infty}(\lambda)]-\mathbb{E}[V^{l}(\lambda)]=(F_{w(n)}(r_n))^{l}(\mathbb{E}[V^{\infty}(\lambda)]-\lambda\tau_d). \quad (5)$$

From (5) with l and (5) with $l+1$, we have

$$\begin{aligned}&\mathbb{E}[V^{l+1}(\lambda)]-\mathbb{E}[V^{l}(\lambda)]\\ &\quad=(F_{w(n)}(r_n))^{l}(1-F_{w(n)}(r_n))(\mathbb{E}[V^{\infty}(\lambda)]-\lambda\tau_d). \quad (6)\end{aligned}$$

Thus, if $\mathbb{E}[V^{\infty}(\lambda)]\geq\lambda\tau_d$, from (6) we have $\mathbb{E}[V^{1}(\lambda)]\leq\mathbb{E}[V^{2}(\lambda)]\leq\ldots\leq\mathbb{E}[V^{\infty}(\lambda)]$, which means the optimal second-hop strategy should be: the relay keeps probing the second-hop channel until the achievable rate is not less than R_n. On the other hand, if $\mathbb{E}[V^{\infty}(\lambda)]<\lambda\tau_d$, from (6) we have $\mathbb{E}[V^{1}(\lambda)]>\mathbb{E}[V^{2}(\lambda)]>\ldots>\mathbb{E}[V^{\infty}(\lambda)]$, which means the optimal second-hop strategy should be: the relay probes the second-hop channel only once, and transmits if the achievable transmission rate is not less than R_n, or gives up otherwise.

IV. Strategy for the First Hop

Based on the derived optimal second-hop strategy, now we derive an optimal strategy for the first hop. In the first hop, at observation n, when the RTS of the winner source denoted as $w(n)$ is received by its relay and the first-hop channel SNR denoted as $r_f(n)$ is estimated, the decision is either give-up or stop (i.e., to transmit), whichever has higher reward. If the decision for the first hop is give-up, the net reward is $-\lambda\tau_{CTS}$ (since a CTS is needed to notify the decision); if the decision for the first hop is to transmit, the net reward is $\max\{\mathbb{E}[V^{1}(\lambda)],\mathbb{E}[V^{2}(\lambda)],\ldots,\mathbb{E}[V^{\infty}(\lambda)]\}-\lambda(\tau_{CTS}+\tau_d)$, in which $\tau_{CTS}+\tau_d$ is time cost in the first hop: the relay uses a CTS to notify the source of the decision and the source transmits with τ_d duration.

First consider $\mathbb{E}[V^{\infty}(\lambda)]<\lambda\tau_d$ for the second hop. Then from Section III, $\max\{\mathbb{E}[V^{1}(\lambda)],\mathbb{E}[V^{2}(\lambda)],\ldots,\mathbb{E}[V^{\infty}(\lambda)]\}=\mathbb{E}[V^{1}(\lambda)]$. So the net reward of transmission in the first hop is $\mathbb{E}[V^{1}(\lambda)]-\lambda(\tau_{CTS}+\tau_d)$. Since $\mathbb{E}[V^{\infty}(\lambda)]<\lambda\tau_d$, from (5) with $l=1$ we have

$$\mathbb{E}[V^{1}(\lambda)]=(1-F_{w(n)}(r_n))\mathbb{E}[V^{\infty}(\lambda)]+F_{w(n)}(r_n)\lambda\tau_d<\lambda\tau_d$$

which leads to $\mathbb{E}[V^{1}(\lambda)]-\lambda(\tau_{CTS}+\tau_d)<-\lambda\tau_{CTS}$. In other words, the net reward of transmission in the first hop is less than the net reward of give-up in the first hop, and thus, the winner source will always give up in the first hop. Therefore, when we calculate the net reward of transmission in the first hop, we can ignore "$\mathbb{E}[V^{\infty}(\lambda)]<\lambda\tau_d$". Thus, we focus on $\mathbb{E}[V^{\infty}(\lambda)]\geq\lambda\tau_d$, and from Section III, the net reward of transmission (stopping) in the first hop is

$$\begin{aligned}&\mathbb{E}[V^{\infty}(\lambda)]-\lambda(\tau_{CTS}+\tau_d)\\ &\overset{(a)}{=}R_n\tau_d-\frac{1}{1-F_{w(n)}(r_n)}\lambda\tau_2-\lambda(\tau_{CTS}+\tau_d) \qquad (7)\\ &\overset{(b)}{=}\tau_d\log_2(1+r_n)-\lambda\tau_{CTS}-\lambda\tau_d-\lambda e^{\frac{r_n}{\rho_{w(n)}}}\tau_2\end{aligned}$$

in which (a) comes from $\mathbb{E}[V^{\infty}(\lambda)]=R_n\tau_d-\frac{\lambda\tau_2}{1-F_{w(n)}(r_n)}$ which is from (4) with $l=1$, and (b) is from $F_{w(n)}(r_n)=1-e^{-\frac{r_n}{\rho_{w(n)}}}$ (Rayleigh fading) and $r_n\triangleq 2^{R_n}-1$. The net reward (7) is not a monotonically increasing function of r_n. Next we set up an optimal r_n that makes the net reward maximal.

For winner source $w(n)$, define function $\phi(x_{w(n)})=\tau_d\log_2(1+x_{w(n)})-\lambda\tau_{CTS}-\lambda\tau_d-\lambda e^{x_{w(n)}/\rho_{w(n)}}\tau_2$, which is a concave function of $x_{w(n)}$. To find the optimal $x_{w(n)}$, denoted $x^*_{w(n)}$, that maximizes $\phi(x_{w(n)})$, we can solve $\frac{d\phi(x_{w(n)})}{dx_{w(n)}}=0$, which leads to

$$\frac{\tau_d}{(1+x^*_{w(n)})\ln 2}=\frac{\lambda}{\rho_{w(n)}}e^{\frac{x^*_{w(n)}}{\rho_{w(n)}}}\tau_2. \quad (8)$$

$x^*_{w(n)}$ can be calculated from (8) numerically. So r_n should be set to $x^*_{w(n)}$ if feasible. However, it may not be feasible to set r_n to be $x^*_{w(n)}$ since r_n should be not more than the first-hop channel SNR $r_f(n)$. Thus, overall we should set $r_n=\min\{r_f(n),x^*_{w(n)}\}$ and $R_n=\log_2(1+\min\{r_f(n),x^*_{w(n)}\})$.

Recall that an optimal stopping strategy of Problem (2) with λ^* satisfying $U(\lambda^*)=0$ is an optimal stopping strategy of Problem (1). So next we focus on optimal stopping strategy of Problem (2) with λ^*. Maximal expected reward $U(\lambda^*)$ of Problem (2) should satisfy an optimality equation [7]:

$$\begin{aligned}&\sum_{w(n)=1}^{M}\frac{1}{M}\mathbb{E}_{w(n)}\big[\max\big\{\tau_d\log_2(1+\min\{r_f(n),x^*_{w(n)}\})\\ &-\lambda^*(\tau_{CTS}+\tau_d+e^{\frac{\min\{r_f(n),x^*_{w(n)}\}}{\rho_{w(n)}}}\tau_2),\ U(\lambda^*)-\lambda^*\tau_{CTS}\big\}\big]\\ &\qquad-\lambda\tau_1=U(\lambda^*)\end{aligned}$$

in which $1/M$ is the probability for a source to be the winner source, and $\mathbb{E}_{w(n)}[\cdot]$ means expectation when $r_f(n)$ follows Rayleigh fading with mean SNR being $\eta_{w(n)}$ (i.e., source $w(n)$ is the winner source). λ^* can be calculated numerically from the optimal equation by setting $U(\lambda^*)=0$.

Accordingly, an optimal stopping strategy for winner source $w(n)$ in the first hop is given as

$$\begin{aligned}&N^*(\lambda^*)=\min\big\{n\geq 1:\ \tau_d\log_2(1+\min\{r_f(n),x^*_{w(n)}\})\\ &-\lambda^*(\tau_{CTS}+\tau_d+e^{\frac{\min\{r_f(n),x^*_{w(n)}\}}{\rho_{w(n)}}}\tau_2)\geq-\lambda^*\tau_{CTS}\big\} \quad (9)\end{aligned}$$

in which $x^*_{w(n)}$ can be calculated from (8) with $\lambda=\lambda^*$.

For each winner source $w(n)$, the left-hand side of the inequality in (9) is a non-decreasing function of $r_f(n)$. Denote $\hat{r}_{f,w(n)}$ as the solution of $r_f(n)$ that makes two sides of the inequality in (9) equal. Then the optimal stopping strategy in the first hop is rewritten as $N^*(\lambda^*)=\min\big\{n\geq 1:\ r_f(n)\geq\hat{r}_{f,w(n)}\big\}$. Overall, the proposed scheme works as follows. After a successful channel contention, winner source $w(n)$'s relay compares the first-hop channel SNR $r_f(n)$ with the threshold $\hat{r}_{f,w(n)}$: if $r_f(n)<\hat{r}_{f,w(n)}$, the first-hop decision is give-up; otherwise, the first-hop decision is stopping, i.e., source $w(n)$ transmits with rate $R_n=\log_2(1+\min\{r_f(n),x^*_{w(n)}\})$. Subsequently the relay keeps probing the second-hop channel and comparing the second-hop achievable rate with R_n. If the second-hop achievable rate is larger than R_n, the relay transmits; otherwise, the relay keeps probing and comparing until it transmits eventually. Note that the values of $\hat{r}_{f,w(n)}$ and $x^*_{w(n)}$ for $w(n)=1,2,\ldots,M$ can be calculated off-line, and thus, only one comparison is needed for the first-hop decision and a few comparisons are needed for the second-hop decision. Similarly, for the scheme in [6], only a few comparisons are needed in its two-level decisions. Thus, the computation complexity in each scheme is very low, and can be expressed as $O(1)$ since the complexity is not a function of the number of users.[1]

V. Performance Evaluation

We use simulation to evaluate the proposed scheme, the scheme in [6] (with direct links not considered), and a naive scheme that utilizes all transmission opportunities (which is actually the scheme in [6] that never gives up in the first and second level decisions). The simulated network has 18 source-destination pairs, with other parameters as: system bandwidth is 2MHz, $\sigma = 20\mu$s, $\tau_{RTS} = 103\mu$s, $\tau_{CTS} = \tau_{timeout} = 106\mu$s, $\tau_d = 8$ms, $p = 0.1$, $\eta_i = 1\ \forall i$, $\rho_i = \rho\ \forall i$. We vary the second-hop average SNR ρ from 1 to 20.

Consider that each source has an infinitely backlogged queue. Fig. 1 shows the system throughput of the three schemes. Our scheme and the scheme in [6] have much better performance than the naive scheme. When ρ is below 5, the scheme in [6] achieves higher system throughput (for example, when $\rho = 2$, throughput of the scheme in [6] is 28% higher than that of our scheme). When $\rho > 5$, our scheme achieves better throughput performance (for example, when $\rho = 20$, throughput of our scheme is 14% higher than that of the scheme in [6]). Fig. 1 also shows the average number of second-hop probings per transmission in our scheme. The number is not large, and decreases when ρ increases.

Now we evaluate delay performance which is important for delay-sensitive applications. Since delay-sensitive applications often have periodic traffic arrivals, we consider that each source has periodic packet arrivals with packet inter-arrival duration being 10 ms. Each packet has 500 bits. Define *packet delay* as the duration from a packet arrival until the moment when the packet is transmitted. Fig. 2 shows average packet delay in the three schemes. When $\rho = 1$, the traffic load is more than the system capacity, and thus, the packet delay is large in the three schemes. When ρ increases, the system capacity increases, and the packet delay decreases. For $\rho \geq 2$, the packet delay of our scheme and the scheme in [6] are similar and are less than 10% of that in the naive scheme. This is because, by giving up transmission opportunity (in our scheme and the scheme in [6]) and/or letting relays wait (in our scheme), each transmission can have a higher rate, and thus, queueing delay in the system decreases.

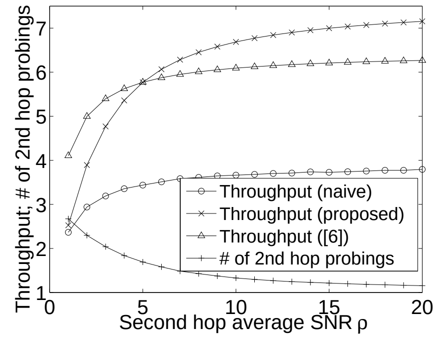

Fig. 1: Throughput (unit: 0.2 Mbps) of three schemes, and average number of second-hop probings per transmission in our scheme.

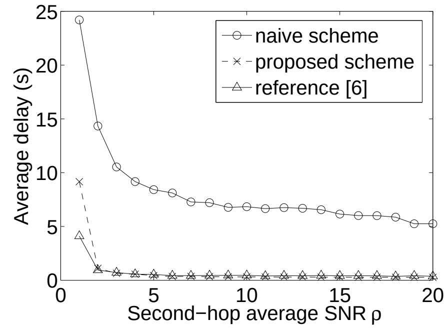

Fig. 2: Average packet delay.

Overall, an adaptive scheme can work as follows. By normalizing the first-hop average SNR to be 1, the curves of system throughput vs. second-hop average SNR ρ can be numerically plotted off-line for our scheme and the scheme in [6], similar to plotting the two upper curves in Fig. 1. The intersection of the two curves gives a threshold $\rho^{\dagger}$ (which is approximately 5 in the example of Fig. 1). Then our scheme should be used when ρ is more than $\rho^{\dagger}$, and the scheme in [6] should be used otherwise. This adaptive scheme can achieve good performance in low to high SNR.

[1]In this work, we focus on throughput maximization. Thus, sources with good average channel gains get more chances to transmit. If fairness is also required, the following modification can be taken. First consider an *imaginary network* with independent and identically distributed (i.i.d.) first-hop channels with mean SNR being $(\sum_{i=1}^{M} \eta_i)/M$ and i.i.d. second-hop channels with mean SNR being $(\sum_{i=1}^{M} \rho_i)/M$. Then our scheme is applied to find optimal strategies for the two hops. The first-hop strategy is to compare $r_f(n)$ with a threshold that is common for all sources. We can calculate the probability that a winner source will stop (the probability that the first-hop instantaneous SNR is not less than the threshold), denoted as α. Then, for the real network, for the first-hop, the threshold for source i is set up such that the probability that source i's first-hop instantaneous SNR is not less than the threshold is equal to α; and if the first-hop decision is stopping, the relay keeps probing the second hop until a good enough second-hop channel is observed. By this setting, each source has the same chance in channel access.

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